IDŐJÁRÁS

QUARTERLY JOURNAL
OF THE HUNGARIAN METEOROLOGICAL SERVICE

CONTENTS

VOL. 99 * NO. 1 * JANUARY–MARCH 1995

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

Editor-in-Chief
G. MAJOR

Editor
T. TÄNCZER

Technical Editor
Ms. M. ANTAL

Editorial Office: P.O. Box 39, H-1675 Budapest, Hungary

Subscription from customers in Hungary should be sent to the Financial Department of the Hungarian Meteorological Service Kitaibel Pál u. 1, 1024 Budapest. The subscription rate is HUF 2500.

Abroad the journal can be purchased from the distributor: KULTURA, P.O. Box 149, H-1389 Budapest. The annual subscription rate is USD 55.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 1, January–March 1995

Predictability of nonlinear dynamical systems

G. Götz

Lupény utca 6-8, H-1026 Budapest, Hungary

(Manuscript received 22 December 1994; in final form 30 January 1995)

Abstract—One of the basic tenets of science is that deterministic systems are predictable: given the initial condition and the equations describing a system, the behaviour of the system can be predicted for all time. The recent discovery of chaotic systems has eliminated this viewpoint. A chaotic system is a deterministic system that exhibits aperiodic behaviour. Another property of a chaotic system is sensitive dependence on initial conditions. Therefore, no matter how precisely the initial conditions are known, the long-term behaviour of a chaotic system can never be predicted. Chaos can readily occur in all dynamical systems where nonlinearity is present: the required dimensionality of the system is only three for autonomous continuous-time systems, two for invertible discrete-time systems, and one for noninvertible discrete-time systems.

Following a short historical review of the problem of predictability, we outline some quantitative measures of chaotic behaviour: the Lyapunov exponents, the metric entropy, and fractal dimensions. We show that the predictability problem is intrinsically linear in its early stages; nonlinearity affects the evolving basic state that is perturbed and ultimately it also affects the saturation of the perturbation growth. Yet, for sufficiently small perturbations there is an interval in which the tangent linear equations are valid.

Dynamical systems theory has provided a new quantitative perspective on the predictability of weather and climate processes. The analysis of model-generated and observational time series confirmes the existence of intrinsically imposed limits of atmospheric predictability. Introduction of ensemble forecast techniques is an explicit recognition that the atmosphere exhibits random behaviour. At the end of this review article, the basic concept of ensemble prediction is outlined with special emphasis on the selection of optimal perturbations.

Key-words: chaos, Lyapunov exponents, metric entropy, fractal dimensions, ensemble prediction.

1. Introduction

The question of *predictability* has a long history in physics. Following the formulation of the classical deterministic laws of mechanics by Isaac Newton in the 17th century, many scientists had a fundamental belief that once one had determined the laws governing the Universe, it was just a matter of solving the equations, with appropriate starting conditions, to discover its past and future behaviour. The most extreme form of this doctrine was strikingly expounded by Pierre Simon de Laplace in the 19th century. He envisaged a supreme intelligence in his *Essai philosophique sur les probabilités* (1814): 'Such an intelligence would embrace in the same formula the movements of the greatest bodies of the Universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.'

Then, in the 1920s, quantum mechanics came along. At the heart of quantum physics lies Heisenberg's uncertainty principle, which states that it is impossible to determine with accuracy both the position and the momentum of a particle, and therefore everything we can measure is subject to truly random fluctuations. Quantum fluctuations are not the result of human limitations or hidden degrees of freedom; they are inherent in the working of nature on atomic scales. Quantum mechanics has thus introduced *probability* and *randomness*, i.e. an element of *genuine unpredictability* at a fundamental level into physics, that greatly upset Albert Einstein: 'God does not play dice', he said.

Then, surprisingly, the modern study of nonlinear dynamical systems from the 1960s has shown us that even the classical Newtonian physics has randomness and unpredictability at its core. Numerical simulations — playing a crucial role in the process of finding and analysing nonlinear phenomena, and becoming more and more wide-spread with the recent availability of digital computing power — have revealed that deterministic systems may exhibit random behaviour.[1] We now know that such a strange behaviour, also called *chaos*, can readily occur in all systems where *nonlinearity* is present. Indeed, chaos has been reported from virtually every scientific discipline, including even mathematics: there are theorems connected with the most traditional branch of pure mathematics, number theory, that cannot be proved because when we ask questions, we obtain results that are equivalent to the random toss of coin.

There is no generally accepted definition of chaos. We know that a chaotic spectrum is not composed solely of discrete frequencies, but has a continuous, broad-band nature. We also know that the attracting limit set for chaotic behaviour is not a simple geometrical object like a circle or a torus, but is related to fractals and Cantor sets. Another property of chaotic systems is *sensitive dependence on initial conditions*: given two different initial conditions arbitrarily close to one another, the phase-space trajectories emanating from these points diverge at a rate characteristic of the system until, for all practical purposes, they are uncorrelated. This divergence is determined by the system's internal dynamical instabilities associated with the part of the phase space

---

[1]There are random events in nature, but science has typically used *probabilistic* models to describe them.

through which the trajectories evolve. In practice, the initial state of a system can never be specified exactly, but only to within some tolerance $\epsilon(0) > 0$; if two initial conditions $x_1(0)$ and $x_2(0)$ lie within $\epsilon(0)$ of one another, they cannot be distinguished. However, after a finite amount of time, $x_1(t)$ and $x_2(t)$ will diverge and become unrelated (*Fig. 1*). Therefore, no matter how precisely the initial condition is known, the long-term behaviour of a chaotic system can never be predicted. (Of course, in theory, if the initial condition could be specified to infinite precision, the phase-space trajectory of a mathematical dynamical system could be predicted precisely.)

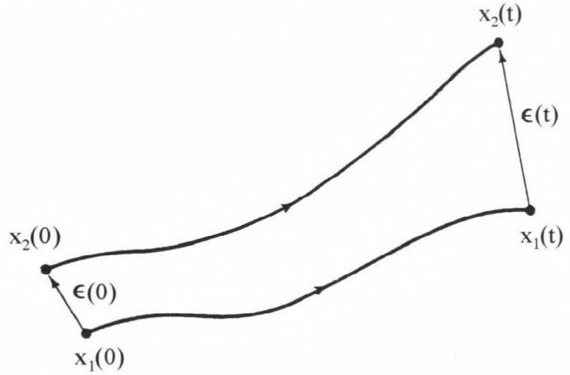


Fig. 1. Evolution of two nearby trajectories in phase space.

It should be noted that there were classical physicists and mathematicians, even in the previous century, who had thought about nonlinear dynamical systems. Jacques Hadamard first observed the sensitivity of solutions to initial conditions at the end of the last century in a rather specific system called geodesic flow. Subsequently, J. Henri Poincaré discussed in 1908 sensitivity to initial conditions and unpredictability at the level of scientific philosophy. Poincaré even went on to discuss the problem of weather predictability. However, their ideas seem to have been forgotten until *Lorenz* (1963) rediscovered them independently in his elegant paper more than half a century later.

It is quite understandable that in the meanwhile atmospheric scientists have focussed their attention mainly on looking for attainable methods of predicting the weather. It became soon obvious that no simple set of causal relationships can be found which relate the state of the atmosphere at one instant of time to its state at another. It was this realization that led *Vilhelm Bjerknes* (1904) to define the *theoretical* problem of prognosis in terms of the Newtonian physics: 'If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceding ones according to physical laws, then it is apparent that the necessary and sufficient conditions for the rational solution of the forecasting problem are the following: (1) A sufficiently accurate knowledge of the state of the atmosphere at the initial time. (2) A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another.'

But it remained for *Lewis F. Richardson* (1922) to suggest the *practical* means for the solution of this problem: he proposed to integrate the equations of motion *numerically,* and showed how this might be done. That the actual forecast used to test his method was unsuccessful was in no sense a measure of the value of his work. Then, for a long time, no one ventured to follow Richardson's footsteps. It was only 25 years later, with the increase in density and extent of the observational network on the one hand, and the development of high-speed computing machines on the other, that an international meteorological working group at the Institute for Advanced Study in Princeton, New Jersey could adopt a general plan of attacking the problem of numerical weather prediction by a step by step investigation of a series of simplified models of the atmosphere (*Charney et al.*, 1950; *Charney*, 1951).

Questions of predictability were not in the forefront of interest in those days, although O. G. Sutton warned in 1951 that the weather problem might be inherently unsolvable because of very small random influences having great effects within unstable systems in the atmosphere. In 1953, P. Raethjen considered the atmosphere nearly always to be in the situation of 'a Hercules at the cross-roads'. He pointed out that even minute influences may suffice to change a stable atmosphere into an unstable one when the state passes a certain threshold value; and then a 'decision' with fundamental consequences may in its turn be triggered. 'The manifold instability of the atmosphere will always remain an invincible hindrance to a physically founded and exact weather forecasting,' Raethjen said (see *Bergeron*, 1959).

The words *classical predictability studies* now usually refer to those works in which an attempt is made to arrive at a qualitative estimate of the growth rate of an individual error and to determine the limits of predictability. In these studies, either simple models of the atmospheric flow or complex models of the general circulation of the atmosphere with explicit treatments of thermal and mechanical forcings are used. The first such study reported in the literature is the one by *Thompson* (1957) who showed, using a simple barotropic model, that the initial errors tend to grow with time and that the atmospheric flow is not predictable beyond a week. A review of the subsequent attempts to determine the limits of atmospheric predictability along this line can be found in the article by *Shukla* (1985).

The recent (within the last twenty-five years) discovery of chaotic systems has given birth to a rapidly developing interdisciplinary field of research called *nonlinear dynamics*. The investigation of the inherent forecasting limitation in fluid-flow problems is currently one of the most exciting topics in nonlinear systems research. The purpose of this paper is to look over the new quantitative perspective on predictability provided by dynamical systems theory and to illustrate how the numerical weather prediction problem can be handled in the light of the new findings.

2. *Quantitative measures of chaos*

Considering the question of the required dimensionality of a system for chaos, we must distinguish between discrete-time dynamical systems and dynamical systems in which time is a continuous variable. A *discrete*, *integer-valued* time dynamical system is defined by the state equation

$$\mathbf{x}_{k+1} = \mathbf{M}(\mathbf{x}_k), \tag{1}$$

where k denotes the time variable ($k = 0,1,2,\ldots$), the state $\mathbf{x}$ is an n-dimensional vector $\mathbf{x}_k = (x_k^{(1)}, x_k^{(2)},\ldots, x_k^{(n)})$, and $\mathbf{M}$ maps the state $\mathbf{x}_k$ to the next state $\mathbf{x}_{k+1}$. If the map $\mathbf{M}$ is noninvertible, i.e. if given $\mathbf{x}_{k+1}$, we cannot solve Eq. (1) for $\mathbf{x}_k$, chaos is possible even in one-dimensional maps. A famous example is the logistic map $x_{k+1} = rx_k(1 - x_k)$, which exhibits chaos for large enough control parameter r. If the map $\mathbf{M}$ is invertible, there can be no chaos unless $n \geq 2$.

An example of a dynamical system in which time t is a *continuous* variable is a system of n first-order ordinary differential equations, which we can write in vector form as

$$d\mathbf{x}/dt = \mathbf{f}(\mathbf{x}), \tag{2}$$

where $\mathbf{x}$ is again an n-dimensional state vector, and since the vector field $\mathbf{f}$ does not depend on time, Eq. (2) defines an autonomous dynamical system. It is common to refer to a continuous-time dynamical system as a *flow*. In the case of (2), $n \geq 3$ is the sufficient condition for chaos to be possible. For example, according to the Poincaré-Bendixon theorem, the only possible attracting solutions of (2) for $\mathbf{x}$ a two-dimensional vector in the phase plane are periodic solutions, steady states and solutions in which the phase-plane trajectory approaches a figure '8' or one of its lobes; in all these cases, the behaviour of the system is not chaotic (*Hirsch* and *Smale*, 1974).

In order to make the notion of 'sensitive dependence on initial conditions' quantitative, different measures have been introduced. A concise survey of these measures is the subject of the following subsections; for a more detailed discussion, the reader is referred to the work by *Ott* (1993).

2.1 *Error growth and Lyapunov exponents*

The mathematical formulation of sensitivity to initial conditions, entailing the growth of small initial perturbations (errors), has been provided by *Oseledec*

(1968). Oseledec's multiplicative ergodic theorem guarantees the existence of a *globally averaged* rate of exponential divergence under very general circumstances; it is referred to as the (largest) *Lyapunov exponent* and is an invariant of the whole dynamical system (see, for example, *Ruelle*, 1989).

Let $\mathbf{x}(0)$ be an initial condition at time 0 and $\mathbf{x}(t)$ the corresponding solution to the real n-dimensional dynamical system (2) for $t > 0$. If we consider an infinitesimal departure from the initial condition $\mathbf{x}(0)$ denoted by $\delta\mathbf{x}(0)$ then, according to the linear stability theorem, the temporal evolution of this initial perturbation is approximately governed by the linearized counterpart of Eq. (2) which can be written as

$$\frac{d}{dt}\delta\mathbf{x}(t) = \boldsymbol{J}(t) \cdot \delta\mathbf{x}(0) . \tag{3}$$

Here $\boldsymbol{J}(t)$ denotes the $n \times n$ Jacobian matrix of the partial derivatives of $\mathbf{f}(\mathbf{x})$ evaluated at some time t with respect to the initial condition $\mathbf{x}(0)$:

$$\boldsymbol{J}(t) = \begin{bmatrix} \dfrac{\partial f^{(1)}}{\partial x^{(1)}} & \dfrac{\partial f^{(1)}}{\partial x^{(2)}} & & \dfrac{\partial f^{(1)}}{\partial x^{(n)}} \\ \dfrac{\partial f^{(2)}}{\partial x^{(1)}} & \dfrac{\partial f^{(2)}}{\partial x^{(2)}} & \cdots & \dfrac{\partial f^{(2)}}{\partial x^{(n)}} \\ & \cdot & & \\ & \cdot & & \\ & \cdot & & \\ \dfrac{\partial f^{(n)}}{\partial x^{(1)}} & \dfrac{\partial f^{(n)}}{\partial x^{(2)}} & & \dfrac{\partial f^{(n)}}{\partial x^{(n)}} \end{bmatrix} ,$$

i.e. one can write Eq. (3) in the scalar form as

$$\frac{d}{dt}\delta x^{(i)} = \sum_{j=1}^{n} \frac{\partial f^{(i)}}{\partial x^{(j)}} \delta x^{(j)} \qquad (i = 1,2,\ldots,n) , \tag{4}$$

in which the coefficients $\partial f^{(i)}/\partial x^{(j)}$ are in general a function of time. The linear system of equations (3) is called the *tangent linear system* of (2) in the vicinity of the basic state $\mathbf{x}(t)$.

Integrating Eq. (3) over some portion of the phase-space trajectory $\mathbf{x}$ between times 0 and t, we obtain

$$\delta\mathbf{x}(t) = \boldsymbol{A}(t) \cdot \mathbf{x}(0)\,, \tag{5}$$

where the $n \times n$ linear operator $\boldsymbol{A}(t)$ is the matrix solution of the equation $d\boldsymbol{A}/dt = \boldsymbol{J} \cdot \boldsymbol{A}$ subject to the initial condition $\boldsymbol{A}(\mathbf{x}(0),0) = \boldsymbol{I}$ ($\boldsymbol{I}$ denoting the $n \times n$ identity matrix). Thus, $\boldsymbol{A}(t)$ depends upon the values of $\mathbf{x}$ between times 0 and t, and controls the growth of small perturbations during this time interval. Therefore, the evolution operator $\boldsymbol{A}$ is often referred to as the *error matrix*. If the variations in the basic state between times 0 and t are neglected, so that $\boldsymbol{J}(t)$ is constant, one can write

$$\boldsymbol{A}(t) = e^{\boldsymbol{J}(t)}\,. \tag{6}$$

We call the vectors $\delta\mathbf{x}(t)$ *tangent vectors* of the system, and the space in which they lie the *tangent space* to $\mathbf{x}(t)$. Eq. (5) describes the sum of all perturbations that are of normal-mode form. In general, the n eigenvalues of the matrix $\boldsymbol{A}$ are either real or else occur in complex conjugate pairs. The normal modes in (5) are, therefore, growing, decaying, or oscillatory depending on the type of the ith eigenvalue. Furthermore, due to the possible asymmetry of the Jacobian $\boldsymbol{J}(t)$, which is always the case for realistic basic-state flows, the eigenvectors of $\boldsymbol{A}$ are not necessarily orthogonal to each other, a fact that has an important impact on the initial evolution of small perturbations, as it will be discussed in Section 3.

Let us now consider the evolution of the initial departures (errors) on the surface of an n-dimensional hypersphere with a radius of ϵ:

$$\delta\mathbf{x}^{\mathrm{T}}(0) \cdot \delta\mathbf{x}(0) = \epsilon^2, \tag{7}$$

where T denotes the transpose of a matrix. As each error in the ensemble is allowed to evolve according to Eq. (5), this sphere will be deformed at time t into an ellipsoid given by

$$\delta\mathbf{x}^{\mathrm{T}}(t)\,[\boldsymbol{A}(t) \cdot \boldsymbol{A}^{\mathrm{T}}(t)]^{-1}\,\delta\mathbf{x}(t) = \epsilon^2. \tag{8}$$

Whilst in general $\boldsymbol{A}(t)$ is not symmetric, by construction the product operator $\boldsymbol{A}(t) \cdot \boldsymbol{A}^{\mathrm{T}}(t)$ is, and possesses n real non-negative eigenvalues. If these are denoted by $\gamma_i^2(t)$ and ordered such that $\gamma_1^2(t) \geq \gamma_2^2(t) \geq \ldots \geq \gamma_n^2(t)$, then the principal axes of the error ellipsoid at time t will be $\epsilon\gamma_1, \epsilon\gamma_2, \ldots, \epsilon\gamma_n$. Thus γ_i, which are by definition the singular values of the error matrix $\boldsymbol{A}$, correspond to the factors by which the components of an infinitesimal deviation $\delta\mathbf{x}(0)$ from the initial condition $\mathbf{x}(0)$ grow ($\gamma_i > 0$) or shrink ($\gamma_i < 0$) in the phase space parallel to the respective orthogonal singular vectors of $\boldsymbol{A}$. In other words, the fastest growing perturbations are the eigenvectors belonging to the largest eigenvalues of the product operator $\boldsymbol{A} \cdot \boldsymbol{A}^{\mathrm{T}}$.

If the limits

$$l_i = \lim_{t \to \infty} \left[\gamma_i(t)\right]^{1/t} \qquad (i = 1,2,\ldots,n) \tag{9}$$

exist, and the positive tth root is taken, these quantities are called *Lyapunov numbers*, while

$$\lambda_i = \ln l_i = \lim_{t \to \infty} \left\{\ln\left[\gamma_i(t)\right]^{1/t}\right\} \qquad (i = 1,2,\ldots,n) \tag{10}$$

define the *Lyapunov exponents* for the initial condition $\mathbf{x}(0)$ and the orientation of the initial perturbation $\delta\mathbf{x}(0)/|\delta\mathbf{x}(0)|$. Eq. (10) can also be expressed in the form

$$\lambda_i = \lim_{t \to \infty} \frac{1}{t} \ln \frac{\delta x^{(i)}(t)}{\delta x^{(i)}(0)} \qquad (i = 1,2,\ldots,n)\,. \tag{11}$$

The ordered set $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$ gives the spectrum of Lyapunov exponents of the nth-order dynamical system. This spectrum is an invariant of the system, independent of the trajectory, except for a set of initial conditions of Lebesgue measure zero (*Parker* and *Chua*, 1987).

In the case of discrete-time dynamical systems (1), all the above considerations carry through with the linearized evolution of the infinitesimal departure from $\mathbf{x}_o$ in the direction of the tangent vector $\delta\mathbf{x}_o$ determined now by

$$\delta\mathbf{x}_{k+1} = \mathbf{DM}(\mathbf{x}_k) \cdot \delta\mathbf{x}_k\,, \tag{12}$$

where $\mathbf{DM}(\mathbf{x}) = \partial\mathbf{M}(\mathbf{x})/\partial\mathbf{x}$ is a Jacobian matrix. From Eq. (12), we have

$$\delta\mathbf{x}_k = \mathbf{DM}^k(\mathbf{x}_o) \cdot \delta\mathbf{x}_o\,, \tag{13}$$

where

$$\mathbf{DM}^k(\mathbf{x}_o) = \mathbf{DM}(\mathbf{x}_{k-1}) \cdot \mathbf{DM}(\mathbf{x}_{k-2}) \cdot \ldots \cdot \mathbf{DM}(\mathbf{x}_o)\,,$$

i.e. $\mathbf{DM}^k$ plays the roles of $\boldsymbol{A}(t)$ in Eq. (5) in the treatment of continuous-time systems, and Eq. (11) is now replaced by

$$\lambda_i = \lim_{k \to \infty} \frac{1}{k} \ln \frac{\delta x_k^{(i)}}{\delta x_o^{(i)}} \qquad (i = 1,2,\ldots,n). \tag{14}$$

From Eqs. (11) and (14) it follows that

$$\delta x^{(i)}(t) \sim \delta x^{(i)}(0)\, e^{\lambda_i t} \tag{15}$$

and

$$\delta x_k^{(i)} \sim \delta x_o^{(i)} e^{\lambda_i k}, \tag{16}$$

i.e., the Lyapunov exponents characterize the temporally averaged (global) exponential rate of divergence ($\lambda_i > 0$) or convergence ($\lambda_i < 0$) of infinitesimally nearby initial states. If $|\delta \mathbf{x}(t)| > |\delta \mathbf{x}(0)|$ for any $t > 0$, the continuous-time system is called *expanding flow*. Thus, positive Lyapunov exponents quantify the long time expansion occurring in a dynamical system. The inverse of the sum of the positive Lyapunov exponents $(\Sigma\lambda_+)^{-1}$ gives an estimate of the mean e-folding time t_e of the initial growth of infinitesimal errors, which is usually looked upon as the deterministic predictability time of the system. (For predictability experiments, the common measure is the mean doubling time t_d of small errors, which is obtained by $(\Sigma\lambda_+)^{-1} \ln 2$.) In this way, positive Lyapunov exponents are a quantitative measure of the average degree of sensitive dependence on initial conditions of the system, or equivalently, the average exponential rate at which deterministic predictive ability is lost.

The sum of the Lyapunov exponents is the average divergence of the flow. For bounded hydrodynamical systems, forcing and quadratic dissipation combine to restrict all trajectories to a closed region of the phase space, i.e., contraction of phase-space volumes outweighs expansion, so

$$\sum_{i=1}^{n} \lambda_i < 0. \tag{17}$$

Thus at least one exponent is negative, and the post-transient motion of trajectories eventually occurs on a zero-volume invariant subset of the phase space, the *system attractor*.

For an illustrative example, we consider a two-dimensional map **M** and sprinkle initial conditions isotropically in a sufficiently small error circle of radius $\epsilon(0)$ around $\mathbf{x}_o$. We suppose that the system is characterized by $\lambda_1 > 0$ ($l_1 > 1$) and $\lambda_2 < 0$ ($l_2 < 1$), and each initial condition evolves under the map **M**.

In this case, k iterations of the map transform the initial error circle approximately into an ellipse with amplifying major radius $\epsilon(0)e^{\lambda_1 k} = \epsilon(0)\, l_1^k$, representing an unstable direction, and decaying minor radius $\epsilon(0)e^{\lambda_2 k} = \epsilon(0)\, l_2^k$, which represents a stable direction in the phase space (*Fig. 2*).

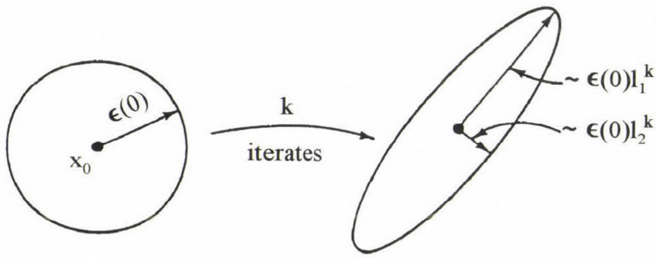


Fig. 2. Evolution of an initially infinitesimal error ball in phase space after k iterations of the map.

If an initial state $\mathbf{x}(t_0)$ and hence $\mathbf{x}(t)$ are on the attractor, the limits in Eq. (10) may be replaced by limits as the initial time $t_0 \rightarrow -\infty$ while t remains fixed. Unit vectors $\mathbf{L}_i$ ($i = 1,2,\ldots,n$) parallel to the principal axes of the error ellipsoid (8) may also approach limits as $t_0 \rightarrow -\infty$. In this case these limits are called the *Lyapunov vectors* at $\mathbf{x}(t)$. As it was shown by *Lorenz* (1984a), hypersurfaces on an attractor extend in the expanding, neutral and contracting local directions of $\mathbf{L}_i$ with positive, zero and negative exponents, respectively.

Lyapunov exponents are convenient for categorizing the consolidated final-state behaviour of dynamical systems. For stable constant solutions, $\lambda_i < 0$ for all i; for stable periodic solutions, $\lambda_1 = 0$ and $\lambda_i < 0$ for $i = 2,3,\ldots,n$; for a two-periodic solution, $\lambda_1 = \lambda_2 = 0$ and $\lambda_i < 0$ for $i = 3,4,\ldots,n$; and for a K-periodic solution, $\lambda_1 = \lambda_2 = \ldots = \lambda_K = 0$ and $\lambda_i < 0$ for $i = K + 1, K + 2,\ldots,n$. The behaviour of these systems is predictable in that small errors in specifying a state point on the respective attractor (fixed point, limit cycle, K-torus) remain constant or decrease over long times. What distinguishes a *chaotic* system from these classical, well-behaved types of deterministic dynamical systems is the existence of at least one *positive* Lyapunov exponent. In the three-dimensional case, $\lambda_1 > 0$, $\lambda_2 = 0$ and $\lambda_3 < 0$. In four-dimensional and higher-dimensional systems, the case of more than one positive Lyapunov exponent has been termed *hyper-chaos*, since there is expansion on the chaotic, or strange attractor in more than one phase-space direction.

We close this subsection by noting that since the Lyapunov exponents are defined in the limit as $t \rightarrow \infty$, any finite transient may be neglected and, therefore, every point in the basin of attraction of an attractor has the same Lyapunov exponents as the attractor. On the other hand, initially nearby trajectories need not diverge at the same rate on *all* parts of a chaotic attractor (*Benzi* and *Carnevale*, 1989). This variability of the *local* divergence rate in phase space can result from the proximity of trajectories to unstable fixed points and unstable manifolds. Clearly, whereas the Lyapunov exponents quantify global, or time-averaged predictability of the flow, the local divergence rates measure the instantaneous predictability as a function of phase-space position (*Abarbanel et al.*, 1991).

If time is written as $t = k\tau$ ($k = 0,1,2,\ldots$), where τ is the time step of the model, then a local divergence rate can be defined as

$$D[\mathbf{x}(k\tau)] = \frac{1}{\tau} \ln \frac{|\delta\mathbf{x}[(k+1)\tau]|}{|\delta\mathbf{x}(k\tau)|}. \tag{18}$$

The largest of the n local divergence rates D_{max} measures local predictability at the phase-space point $\mathbf{x}$ on a time scale equal to τ, and $1/D_{max}$ approximates the e-folding time of local error growth (*Nese*, 1989). This quantity may vary significantly on the attractor, producing alternating periods of enhanced and limited predictability. The averaged $\bar{D}_{max}$ of $D_{max}(t)$ over a trajectory is at least λ_1. The fact that $\bar{D}_{max} \geq \lambda_1$, rather than $\bar{D}_{max} = \lambda_1$, is due to the difference between the two definitions (18) and (11); for a more detailed mathematical explanation, see *Legras* and *Ghil* (1985).

Another measure of the local error growth rate can be defined directly from the eigenvalues γ_i^2 of the matrix $A(t) \cdot A^{T}(t)$ appearing in Eq. (8):

$$\Lambda(t) = \left[\frac{1}{n}\sum_{i=1}^{n} \gamma_i^2(t)\right]^{1/2}, \tag{19}$$

which was introduced by *Lorenz* (1965), and therefore it is often referred to as the *Lorenz index*. $\Lambda(t)$ gives the ensemble average of the linear growth rate of infinitesimally small initial root-mean-square errors. This index depends neidher on the amplitude nor the configuration of the initial perturbation, but directly represents the local instability characteristics of the flow (*Mukougawa et al.*, 1991).

When differential equations are replaced by integral equations along a trajectory for estimating the linear perturbations that have the fastest growth over some finite trajectory segment, the role of the error matrix in Eq. (5) is taken over by an integral propagator operator $\boldsymbol{R}(t_1,t_2)$ of the linearized equations of the dynamical system, integrated between times t_1 and t_2. The divergence rates for finite segments of a trajectory are given by the singular values of $\boldsymbol{R}$, which are equivalent to the eigenvalues of the product operator $\boldsymbol{R}^*\boldsymbol{R}$, where * denotes the adjoint operation. The corresponding phase-space directions associated with the divergence rates are the singular vectors of $\boldsymbol{R}$, equivalent to the eigenvectors of $\boldsymbol{R}^*\boldsymbol{R}$. For very long time intervals $(t_2 - t_1) \rightarrow \infty$, the eigenvalues of $\boldsymbol{R}^*\boldsymbol{R}$ become equal to the Lyapunov exponents associated with the attractor (*Zeng*, 1991; *Buizza et al.*, 1992; *Palmer*, 1993). (Note that because of its very nature, an adjoint operation proceeds from the output of the model at time t_2 to its input at time t_1, which means that the governing equations must be integrated *backwards* in time. Theoretical and numerical problems of integrating adjoint models are mainly related to irreversible physical processes; the details of these problems are beyond the scope of the present paper.)

2.2 *The metric entropy*

Suppose that the state of the system can be measured to within a resolution of ϵ. Assume there are two observers who measure the state of the system at two different times. Observer 1 observes the state at time t_1 to be x_1. Observer 2 measures the state at time $t_2 > t_1$ to be x_2. Which observer knows more about the state of the system, observer 1 or 2?

As we saw in Section 2.1, a chaotic system expands in some directions in the phase space, and the predictive value of the initial condition deteriorates with time. Therefore, it is more accurate to observe the state at time t_2 than to use x_1 to predict the state at time t_2, and the larger $t_2 - t_1$ is, the less the accuracy of the prediction. Now, since observer 2 possesses more information about the state of the system — and the longer one waits to observe the state, the more one learns —, an expanding flow may be thought of as *creating information*.

In information theory, *information* is a quantity describing the degree of uncertainty of the state of the system. *Metric entropy*, introduced by A. N. Kolmogorov and Ya. G. Sinai (and therefore sometimes called the *Kolmogorov entropy* or the *K-S entropy*), is a number measuring the time rate of creation of information as a chaotic trajectory evolves. If the state of the system can be specified to within some tolerance $\epsilon > 0$, and $I(\epsilon,\tau)$ is the gain of information in a time interval τ, then the metric entropy is defined as

$$H = \lim_{\epsilon \to 0} \lim_{\tau \to 0} \frac{I(\epsilon, \tau)}{\tau}. \tag{20}$$

In order to evaluate H, we divide the attractor Γ of the system into r disjoint elements $\Gamma_1, \Gamma_2, \ldots, \Gamma_r$ of size ϵ, and the time into some intervals of length τ. We consider a segment of the trajectory which is known to be on the attractor and contains the observed phase points $x(\tau)$, $x(2\tau)$,..., $x(k\tau)$. Let p_i ($i = 1,2,\ldots,k$) be the probabilities of the chance that the points $x(i\tau)$ fall into the elements Γ_i. In this case

$$H = \lim_{k\to\infty} \lim_{\epsilon\to 0} \lim_{\tau\to 0} \frac{1}{k\tau} \sum_{i=1}^{n} p_i \ln \frac{1}{p_i}. \tag{21}$$

In well-behaved deterministic systems $H = 0$, in stochastic systems $H = \infty$, while in chaotic systems $H > 0$. It has been proven that the metric entropy is at most the sum of the positive Lyapunov exponents,

$$H \leq \Sigma\lambda_+ \tag{22}$$

(see, for example, *Ruelle*, 1989).

If we wish to express H in binary units, we use $\log_2$ instead of ln in Eq. (21). In this case we can interpret H as the gain of information in bits per unit time. Similarly, the sum of the positive Lyapunov exponents, also expressed in binary units, can be interpreted as measuring the rate in bits of information per unit time at which the uncertainty in the specification of initial data is magnified. Therefore, if the initial conditions are known accurately to q bits, then after $q/\Sigma\lambda_+$ time units, on the average, the initial uncertainty will have contaminated the entire attractor.

2.3 *Fractal dimensions*

As it was discussed above, in a chaotic dissipative system the flow does not contract a volume element in all directions, but stretches it in some. For a bounded system, however, the growth of $|\delta\mathbf{x}(t)|$ cannot be exponential forever; exponential growth must cease when $|\delta\mathbf{x}(t)|$ becomes of the order of the attractor size. In order to remain confined to this bounded domain of the phase space, the stretching volume element gets folded at the same time. As a result of the sequence of these stretching and folding processes, chaotic attractors possess a fine multisheeted structure. A closer study shows that the neighbourhood of any point of a chaotic, or strange attractor does not resemble any Euclidean space. Hence, strange attractors are not manifolds and do not have integer dimension. There are several ways to generalize the concept of dimension to this fractional case, and three are presented here.

Cover an attractor Γ with volume elements each with diameter ϵ. Let $N(\epsilon)$ be the number of volume elements needed to cover Γ. The *information dimension* d_I is defined by

$$d_I = \lim_{\epsilon \to 0} \frac{\ln S(\epsilon)}{\ln (1/\epsilon)}, \tag{23}$$

where

$$S(\epsilon) = \sum_{i=1}^{N(\epsilon)} p_i \ln (1/p_i), \tag{24}$$

p_i denoting here the relative frequency with which a typical trajectory enters the ith volume element of the covering (*Farmer et al.*, 1983). Thus information dimension weights a volume element according to how often a trajectory is found in it; volume elements that are visited infrequently have little influence on d_I. Comparing (24) with (21), we recognize $S(\epsilon)$ as entropy — the amount of information necessary to specify the state of the system to within an accuracy of ϵ if the state is known to be on the attractor. Eq. (23) may be rewritten as

$$S(\epsilon) = c(1/\epsilon)^{d_I} \tag{25}$$

for some constant c and sufficiently small ϵ. In words, the amount of information needed to specify the state increases inversely with the d_Ith power of ϵ.

Another probabilistic type of dimension is the *correlation dimension* d_C defined by *Grassberger* and *Procaccia* (1983) as

$$d_C = \lim_{\epsilon \to 0} \left\{ \left[\ln \sum_{i=1}^{N(\epsilon)} p_i^2 \right] [1/\ln \epsilon] \right\}, \tag{26}$$

i.e. it also utilizes information about the time behaviour of the dynamical system. The correlation dimension is computationally very efficient to calculate even for attractors in high-dimensional phase spaces. It can be shown that $d_C \leq d_I$, and also that $n_+ \leq d_C$ for n_+ the number of positive Lyapunov exponents.

The *Lyapunov dimension* d_L of an attractor is defined by *Kaplan* and *Yorke* (1979) in terms of the Lyapunov exponents λ_i of a dynamical system as

$$d_L = j - \frac{\lambda_1 + \lambda_2 + \ldots + \lambda_j}{\lambda_{j+1}}, \tag{27}$$

where j is the largest integer such that $\lambda_1 + \lambda_2 + \ldots + \lambda_j \geq 0$. Thus d_L depends solely on the system dynamics. For a stable limit cycle, $0 = \lambda_1 > \lambda_2 \geq \lambda_3 \geq$

$\ldots \geq \lambda_n$, so $j = 1$ and $d_L = 1$ as expected. Likewise, for a two-torus, $d_L = 2$. In a three-dimensional chaotic dynamical system with λ_+, 0, λ_-,

$$d_L = 2 + \frac{\lambda_+}{|\lambda_-|}. \qquad (28)$$

For an attractor, $\lambda_+ + \lambda_- < 0$, from which it follows that $2 < d_L < 3$.

As is obvious from the definition, Lyapunov dimension is somewhat different from the other two. In fact, it is not even clear that d_L is actually a dimension. The exact relationship between d_L and d_I (and the other dimensions defined to the fractional case) is an active research topic.

Dimension is perhaps the most basic aspect of the attractor of a dynamical system. Generally speaking, the dimension provides a measure of the number of independent modes excited by the system, that is, it gives the minimum number of coupled nonlinear differential equations necessary to describe the system. On the other hand, the fractional part of the fractal dimension measures the 'strangeness' of a chaotic attractor.

3. *Phases of error growth*

Let $\mathbf{x}(t)$ be the instantaneous state vector of a dissipative dynamical system. The system is run for a certain transient period of time until it reaches its attractor Γ. At this moment, which is regarded as the initial time 0, the state $\mathbf{x}(0)$ is slightly perturbed by an error vector $\delta\mathbf{x}(0)$. If the evolution of the initial state $\mathbf{x}(0)$ and the perturbed state $\mathbf{y}(0) = \mathbf{x}(0) + \delta\mathbf{x}(0)$ is followed simultaneously, the *instantaneous error* $E(t)$ at time t is defined by $E(t) = \| \mathbf{y}(t) - \mathbf{x}(t) \|$, where $\| \ldots \|$ denotes the Euclidean norm. Because of the complexity of the dynamics of typical systems of interest, $E(t)$ fluctuates considerably both over time and over the phase space of the system. To relate the error dynamics in an intrinsic manner to the properties of the underlying system and to the structure of its attractor, the evaluation of $E(t)$ is repeated for initial conditions $\mathbf{x}(0)$ running all over the attractor Γ, and the *average error* over all these realizations,

$$< E(t) > = \frac{1}{2\mu(\Gamma)} \int_\Gamma d\mathbf{x}(0) \int_\Gamma \frac{\| \mathbf{y}(t) - \mathbf{x}(t) \|}{\| \mathbf{y}(0) - \mathbf{x}(0) \|} \, d\mathbf{y}(0) \qquad (29)$$

is calculated, where $\mu(\Gamma)$ represents the measure of the phase-space region belonging to the attractor Γ.

The first systematic study of error growth was performed by *Lorenz* (1965). He noted that since the initially infinitesimal perturbations continue to grow while they are still small, they must eventually cease to be small, whereupon the tangent linear equations (3) governing them will no longer hold. The errors have then left the *linear phase of growth* and entered the *nonlinear phase of growth*. During this second phase the growth rate must eventually subside, since ultimately the errors will become only as large as the difference between two randomly chosen states of the system. In other words, an initially infinitesimal isotropic error ball, which was evolving into an ellipsoid during the linear phase, would in the nonlinear phase ultimately take on the structure of the system's attractor.

This conclusion has been confirmed and further refined by later investigations, among others by the numerical experiments on error growth carried out recently by *Nicolis* and *Nicolis* (1991), and *Nicolis* (1992). They integrated dynamical systems of varying complexity, including the logistic map, the Bernoulli map and the Rössler flow (see *Ott*, 1993), as well as the minimal model of the general circulation of the atmosphere designed by Lorenz (see *Götz*, 1994). In all cases essentially the same behaviour could be observed, which may reasonably be summarized by the statement that error growth is an explosive phenomenon following a logistic-like curve (*Fig. 3*). In a wide class of chaotic systems, three different stages can be distinguished:

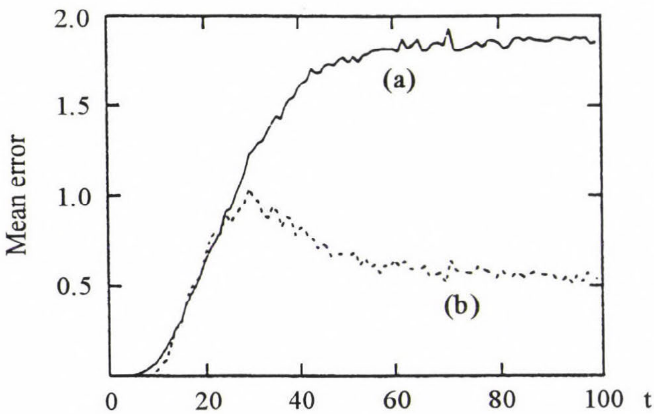


Fig. 3. (*a*) Time-dependence of the root-mean-square error over 1000 realizations for the Lorenz model of the general circulation. (*b*) Time-dependence of the variance of the error around the computed mean. The time unit is equal to five days. (After *Nicolis*, 1992)

(1) A short initial *exponential stage*, where errors remain small and are confined in the tangent space. This stage of error growth reflects local properties of the system and can be easily inferred from the very existence of a positive Lyapunov exponent.

(2) An *intermediate stage* around the inflexion point of the error versus time curve, where error growth displays an approximately linear dependence in time.

(3) A long *final stage* where, owing to the folding mechanism characteristic of chaotic attractors, the mean error reaches a saturation level E_∞ of the order of the extension of the attractor, and remains constant thereafter. The intermediate stage is switched on at a time t^* of the order of $t^* \approx \ln(1/|\delta \mathbf{x}|)$ when errors suddenly become large, they leave the tangent space and perform a diffusive motion on the attractor, while in the final stage errors essentially scan the structure of the attractor as a whole (*Fig. 4*). In this saturation stage, the variance of the cloud of perturbations σ becomes equal to the climate variance of the system σ_c, which means that all deterministic predictability is lost. In practice, one must of course choose some fraction of $\sigma/\sigma_c = 1$ as defining the limit of dynamical predictability, e.g. 0.90 which is consistent with the standard errors of the climate and error variance estimates.

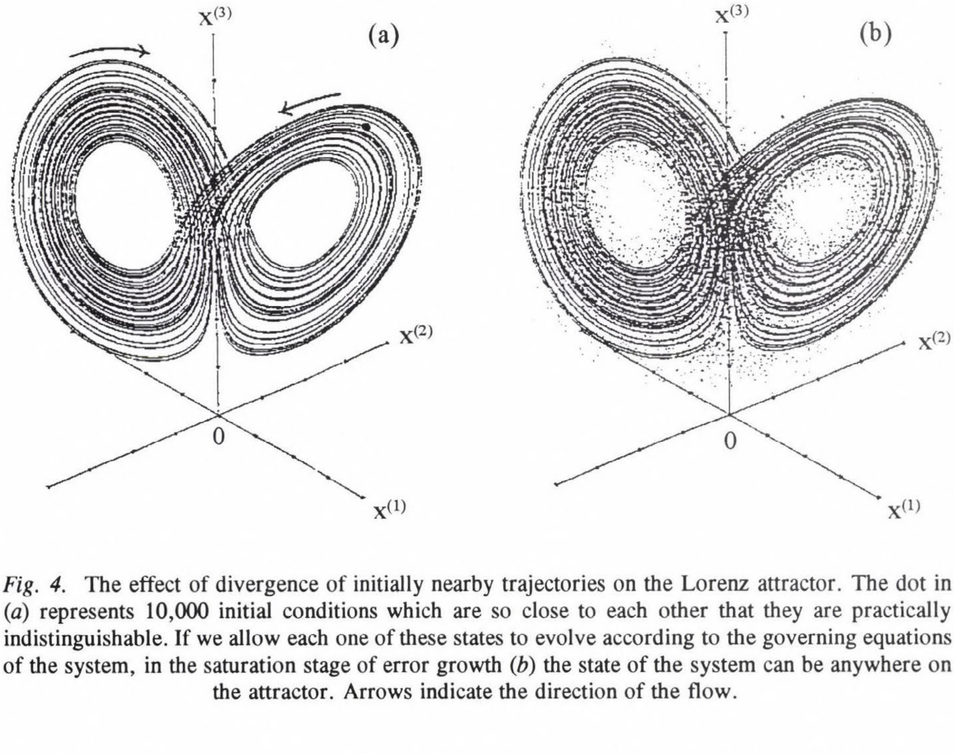


Fig. 4. The effect of divergence of initially nearby trajectories on the Lorenz attractor. The dot in (*a*) represents 10,000 initial conditions which are so close to each other that they are practically indistinguishable. If we allow each one of these states to evolve according to the governing equations of the system, in the saturation stage of error growth (*b*) the state of the system can be anywhere on the attractor. Arrows indicate the direction of the flow.

The first attempt to deduce the law of error growth from real atmospheric data is found in the work of *Lorenz* (1969). From a five-year record of Northern Hemisphere data, Lorenz selected all couples of states (called analogues) that are close enough to each other, that is, whose distance δx can be considered small with respect to the average distance of two randomly chosen states, and then looked at its temporal evolution. Lorenz proposed a quadratic law for the growth of average initial error δx in the simple form of the logistic equation

$$\frac{d}{dt}\delta x = \lambda\,\delta x\,(1 - \delta x)\,. \tag{30}$$

In this error equation, the linear term describes the initial exponential error growth, while the quadratic term enforces saturation at the variance of uncorrelated realizations. Lorenz based the hypothesis of a quadratic law on the argument that the principal nonlinearities governing the atmosphere are quadratic.

The solution of Eq. (30), with initial condition $\delta x(0)$, is

$$\delta x(t) = \frac{1}{1 + [1/\delta x\,(0) - 1]\,\exp(-\lambda t)}\,, \tag{31}$$

which asymptotically tends to the normalized mean distance 1 and shows an exponential growth for small errors with an e-folding time $t_e = 1/\lambda$. Eq. (30) is now often referred to as the *Lorenz's law of error growth*, and the coefficient of the linear term is just the quantity that was introduced some fifteen years later as the *first Lyapunov exponent* of the system (*Farmer et al.*, 1983).

While progress being made in nonlinear dynamics offers hope for a complete theory of predictability including both the intermediate stage and the final saturation stage, well-known methods suffice for understanding only the initial exponential stage by applying linearized small-error theory. Within this context, particular attention has been devoted in recent literature to the finding that the time evolution of initial errors can be actually more involved than outlined above. Within the framework of Oseledec's theory, the error perturbing the initial state of the system is bound to be *infinitesimal*, and therefore the error dynamics is confined in the tangent space, where it must be followed for an *infinitely* long period of time if it is to be related to intrinsic properties of the system. However, when confronted with the problem of predicting the evolution of a concrete physical system, the observer is led to follow the growth of a small but *finite* error over a *finite*, usually short period of time. As shown by *Nicolis* and *Nicolis* (1992), in this more realistic case the first transient phase of error growth is neither exponential, nor driven by the first Lyapunov exponent. They analysed the simple logistic map $x_{k+1} = rx_k$ $(1 - x_k)$ with $r = 4$, i.e. in the region of fully developed chaos. In this system, the value of the Lyapunov exponent is $\lambda = \ln 2$. But for small finite initial errors the authors found that the effective growth rates are highly k-dependent, starting at $k = 1$ with a value significantly larger than ln 2. This transient behaviour, that has been referred to as *superexponential*, entails that for short to intermediate times significant deviations from the Lyapunov-exponent driven exponential error amplification can be expected. This implies in no way a discrepancy with the Oseledec's theory: both the theory and the concept of Lyapunov exponent are perfectly valid, but are unable to account for error dynamics in the relevant regime of small finite errors and finite time.

Whereas transient error growth does not affect the dynamical predictability in the limit of infinitesimally small errors, it may have a dramatic impact on the predictability time for initial errors of a given finite size. As the initial errors cannot be reduced beyond certain limits, this problem may be of great practical importance for numerical weather prediction. Investigations carried out by *Lacarra* and *Talagrand* (1988), *Farrell* (1988, 1989, 1990), *Vukicevic* (1991), *Borges* and *Hartmann* (1992), and *Vannitsem* and *Nicolis* (1994) have revealed that the phenomenon of superexponential error growth is also related to the highly inhomogeneous dynamics on the generally multifractal attractor: during the initial transient phase, mean error amplification is controlled by high-energy perturbations that are not of normal-mode form and exhibit growth-rate values higher than the largest Lyapunov exponent. In order to investigate the impact of the transient error growth on average predictability measures, *Trevisan* (1993) considered the well-known three-dimensional convection model of *Lorenz* (1963). With Lorenz's original choice of parameter values, the spectrum of Lyapunov exponents for this nonlinear dynamical system is $\lambda_1 = 0.90$, $\lambda_2 = 0$, $\lambda_3 = -14.61$. *Fig. 5* shows the growth rate of linear errors as a function of time. During the transient, the ensemble-average error growth rate reaches values much larger than its asymptotic value. After the transient phase of the linear regime, the value of the growth rate stabilizes at about 0.90, in agreement with the value of λ_1 of the system.

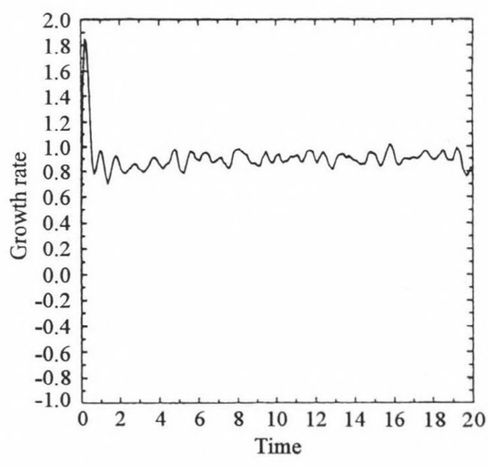


Fig. 5. Growth rate of linear errors as a function of time for the three-dimensional convection model of Lorenz. (After *Trevisan*, 1993)

For many years, it was widely believed that the energetically active synoptic-scale disturbances in the atmosphere arise primarily as exponentially growing normal-mode instabilities of the large-scale background flow. Therefore, the very existence of such a transient phase may be at first sight surprising, and can be explained as follows. For realistic basic-state flows, the error matrix $\boldsymbol{A}$ in Eq. (5) is not symmetric, and hence the eigenvectors of $\boldsymbol{A}$, corresponding to normal modes of dynamical instability, are not typically orthogonal to each other for the phase space of the linearized dynamics. This fact enables superposition of several normal modes to create non-modal perturbations for a limited time that grow very much faster than the most unstable normal-mode perturbation. In more mathematical terms, for non-self-adjoint $\boldsymbol{A}$ the largest singular value of $\boldsymbol{A}$ (from which the largest non-modal error growth rate is inferred) can be much larger than the largest eigenvalue of $\boldsymbol{A}$ (yielding the largest growth rate of the normal modes). Physically it can be argued from both observational and theoretical grounds that the variance associated with synoptic disturbances is connected with non-modal energy transfer from the background flow associated with stochastic forcing, which could arise, for example, from a nonlinear upscale energy cascade (*Farrell*, 1989). Consequently, predictability estimates for synoptic time scales made from the maximum normal-mode growth rate can be erroneously optimistic.

4. Predictability of weather and climate

To facilitate study of the inherently infinite-dimensional partial differential equations governing the forced, dissipative, nonlinear atmospheric flow, spectral techniques are often employed, and the infinite set of transformed equations is truncated to a finite system of n ordinary differential equations. The atmosphere is then represented as an nth-order autonomous dynamical system defined by the state equation (2), in which the components of the state vector $\mathbf{x}(t)$ are the spectral coefficients of a series of orthogonal functions, and the asymptotic solution sets (attractors) of Eq. (2) can be investigated in the more tractable setting of an n-dimensional phase space. The hope is that the essential behaviour characteristics of the atmosphere, for which an infinite number of degrees of freedom is available, can be adequately and faithfully modelled by a deterministic and reasonably low-dimensional system of appropriately chosen modes; for an overview of some of the results, see the article by *Götz* (1994).

In recent years, dynamical systems theory has provided a new quantitative perspective on the predictability of weather and climate processes. The interest in investigations that are using dynamical systems techniques is at least partially rooted in *Lorenz*'s (1965) observation that predictability is a function of the structure of the flow pattern. In addition, the interest in analysing predictability in phase space originates with the remarkable results of the Dynamical Systems

Collective at Santa Cruz, California (*Packard et al.*, 1980), *Ruelle* (1981) and *Takens* (1981) that it may be possible to deduce the unknown attractor of a physical system from a sufficiently long time series of just one state variable, without a knowledge of the evolution laws of the system. Once an attractor is properly reconstructed, the predictability measures discussed in Section 2 can be estimated (*Farmer* and *Sidorowich*, 1987; *Henderson* and *Wells*, 1988).

During the last few years, several researchers have tried to determine these quantitative measures for the atmosphere from model-generated output, as well as from observed data concerning both synoptic and climatic time scales. In this section, main results obtained for predictability limits are summarized.

4.1 Results based on model-generated data

In 1963, Lorenz designed a three-dimensional nonlinear dissipative dynamical system in order to study the Rayleigh-Bénard convection. This low-order truncated spectral model not only correctly represents the initial transition from a conductive to a convective heat transport, but for suitable values of the control parameters it also exhibits the nonperiodic behaviour at more intense thermal forcing, that stimulated Lorenz to lay the foundation of the concept of deterministic chaos. As subsequently calculated by many authors, the correlation dimension of the system's attractor in its chaotic stage (at a slightly supercritical value of the Rayleigh number) is $d_C = 2.05$ with Lyapunov exponents $\lambda_1 = 0.9$, $\lambda_2 = 0$, $\lambda_3 = -14.6$. The average *e*-folding time of small initial errors is $t_e = 1/\lambda_1 = 1.1$ dimensionless time units. *Nese et al.* (1987) extended these calculations to higher-order truncations of the infinite set of ordinary differential equations from which the original Lorenz system is derived. For a seventh-order convection system, at values of the thermal forcing just above the initial transition to aperiodicity, they found $d_L = 4.06$, $H = \Sigma\lambda_+ = 1.43$, and $t_e = 0.7$ time units, while for an eleventh-order system, $d_L = 5.68$, $H = \Sigma\lambda_+ = 1.60$, and $t_e = 0.62$ time units.

Ten years ago, *Lorenz* (1984b) developed a third-order dynamical system as a minimal model of the general circulation of the atmosphere. This nonlinear, geostrophic baroclinic model possesses both Hadley- and Rossby-like solutions. In its chaotic regime, $d_L = 2.35$, $\lambda_1 = 0.18$, $\lambda_2 = 0$, $\lambda_3 = -0.52$, and $t_e = 1/\lambda_1 = 5.5$ time units (about 28 days). By real atmospheric standards, this error amplification is unreasonably small.

The appearance of persistent and recurrent regional weather types (*Grosswetterlagen*) has been long since known to synoptic meteorologists. However, low-order dynamical systems of *Lorenz* (1963, 1984b), *Charney* and *DeVore* (1979), and *Reinhold* and *Pierrehumbert* (1982) have offered the first theoretical explanation of the existence of such distinct flow regimes and the multiple time-scale evolution of the atmosphere in the presence of zonally inhomogeneous external forcing mechanism. There are two time scales associated with these models. The first describes the evolution of the system around the weakly unstable fixed point at the centre of each wing of the Lorenz attractor (Fig. 4), while the second describes a typical residence time within one of the two wings which correspond, qualitatively, to blocked and zonal flow.

Most of the unpredictability of the Lorenz model arises from the divergence of nearby phase-space trajectories in the neighbourhood of the particularly unstable origin (representing the state of rest of the system), and the phase-spatial organization of local predictability is closely connected with the transitions between the flow regimes (*Nese*, 1989; *Mukougawa et al.*, 1991; *Palmer*, 1993). According to *Nese* (1989), in the convection model with Lorenz's original parameter choices, the local divergence rate $D(\mathbf{x})$ varies from -15 bits per nondimensional time unit (bpt) to 16 bpt (note that the largest Lyapunov exponent of the system is λ_1 = 0.9/time unit = 0.9/ln 2 bpt = 1.3 bpt; for synoptic considerations, unit nondimensional time in the model can be taken to correspond to about 10 days in the atmosphere). Adjacent trajectories converge most rapidly on average (D = –5.6 bpt) as they approach the vicinity of the $x^{(3)}$-axis on tops of the attractor wings in Fig. 4. The divergence of initially nearby trajectories increases as they enter the 'splitting' region of the attractor; they diverge most rapidly on average (D = 5.4 bpt) as they swing away from the vicinity of the unstable origin $\mathbf{x} = 0$. The region near the origin is only moderately unpredictable in terms of average local divergence rates (D = 3.8 bpt); nonetheless, when catastrophic separation of initially nearby trajectories occurs, the consequences in terms of forecast errors are extremely severe.

In order to quantify predictability in a more realistic dynamical system, *Legras* and *Ghil* (1985) have introduced a model that is governed by the equivalent-barotropic form of the equation for the conservation of potential vorticity on a sphere, with simplified topography, a forced mid-latitude zonal jet, and Ekman dissipation. The governing equation has been discretized through a truncated expansion in spherical harmonics, and a 25th-order autonomous dynamical system has been derived. The authors have found that as the intensity of the forcing (similar to a Rossby number) is increased (i.e., the validity of the geostrophic approximation is decreased), zonal-dominated sequences of the flow pattern become more and more frequent than blocking-dominated sequences, and the largest Lyapunov exponent of the system increases from λ = 0.028 day^{-1} to λ = 0.095 day^{-1}. Thus, the average e-folding time of small errors decreases by a factor of 3 from t_e = 36 days to t_e = 11 days. The average of local divergence rates of nearby trajectories reveals a local mean e-folding time of errors t_e = 14 days for flows dominated by blocked regimes, which decreases to t_e = 9 days for zonal-dominated regimes. These results are in agreement with observations about the Rossby-number dependence of flow regimes and persistence: blocked regimes are associated with lower Rossby numbers; as the forcing is increased, zonal regimes tend to prevail, the evolution of the flow patterns in physical space is observed to become more rapid and the irregularity of the flow in phase space increases, resulting in a less predictable evolution of the system.

In a recent study of predictability, *Nese* and *Dutton* (1993) used a two-layer moist general circulation model, in which the atmosphere is governed by baroclinic, quasi-geostrophic, mid-latitude, beta-plane dynamics, and the basic state variables are temperature, horizontal wind velocity and isobaric vertical velocity. They found that the correlation and Lyapunov dimensions of the system are $d_C = 5.6$ and $d_L = 6.9$, while the two largest Lyapunov exponents are $\lambda_1 = 0.062$ and $\lambda_2 = 0.004$ bits/day, and thus the average error doubling time is $t_d = 15.1$ days. The sum of the two largest local divergence rates is $D_1(\mathbf{x}(t)) + D_2(\mathbf{x}(t)) = 0.270$ bits/day, i.e., the instantaneous predictability measure is $t_d = 3.7$ days. Activating an oceanic circulation increases the average error doubling times of the atmosphere and the coupled atmosphere-ocean system by 10%, and the local error doubling times to $t_d = 4.4$ days.

Extended (10,000-year) simulations carried out by *Nese* and *Dutton* (1993) enabled them to draw some conclusions concerning the predictability of yearly averaged climatic states. The model exhibited variations in the annually averaged temperature T within a range of about 3 K; changes in T from year to year averaged 0.07 K in magnitude. These changes represent the *natural variability* of the model, since no conditions external to the atmosphere-ocean system were altered. Such warmings and coolings, if encountered in the actual atmosphere, are interpreted as *internal climatic variability*, traditionally regarded as an intrinsically unpredictable component of climatic change. Now, the sum of the positive Lyapunov exponents of the reconstructed attractors has proven to be $H = \Sigma\lambda_+ = 2.04$ bits per year for the inert ocean case, decreasing by 25% to $H = \Sigma\lambda_+ = 1.52$ bits per year when an active ocean circulation is included. These values correspond to average error doubling times of $t_d = 6$ months and $t_d = 8$ months, respectively, i.e. annually averaged climatic states are, indeed, highly unpredictable. On the other hand, one-third of the yearly averaged states have local error doubling times larger than 2 years, indicating that annual climatic states may, at times, be predictable, even without predictable variations in external forcing.

The results summarized above confirm that the oceans have a major influence on weather and climate processes, and profoundly affect the predictability of weather and climate as well. Including a slowly varying component such as an ocean in a weather or climate model enhances the memory of the system and thus improves predictability, especially of time-averaged climatic states. If a circulation is permitted to develop in the model ocean, then the additional inertia in the system further enhances predictability. It has been shown by many investigators that a coupled atmosphere-ocean system is more predictable than the atmosphere alone. *Tribbia* and *Baumhefner* (1988) suggest that fixed lower boundary conditions (such as prescribed sea-surface temperatures) may inhibit the natural equilibration of low-frequency motions through interaction with the underlying surface, thus making interactive boundary-driven motions more predictable than fixed-boundary, externally forced motions.

4.2 Results based on observed data

Following the pioneering work of *Nicolis* and *Nicolis* (1984), several authors have tried to reconstruct weather and climate attracting sets from various sampled time series of single state variables of the atmosphere in order to estimate different predictability measures on attractors, independent of any modelling.

Predictability on synoptic time scales. In an early study, *Fraedrich* (1987) selected daily values of surface pressure, observed at Berlin-Dahlem, for calculating weather predictability. He obtained d_L = 6.8–7.1 for the dimension of the reconstructed attractor, and t_e = 12–17 days for the *e*-folding predictability time scale. *Keppenne* and *Nicolis* (1989) carried out a dynamical systems analysis of atmospheric variability over the entire Western European region, using daily 500-mb geopotential time series from a number of stations. They calculated that two Lyapunov exponents are unmistakingly positive: λ_1 = 0.023 day^{-1}, λ_2 = 0.014 day^{-1}, i.e. one deals here with a hyper-chaotic attractor. The fact that the two positive λ_i are comparable in magnitude suggests that the chaotic dynamics arises from the interference of two independent mechanisms of instability of comparable importance. The mean predictability time for the geopotential signal is t_e = 27 days, which is comparable but clearly larger than that inferred by *Fraedrich* (1987). Considering local rates of divergence, the authors found very strong variability. For values corresponding to low geopotential heights, the predictability is of the order of 30 days; it decreases to about 2 weeks for high geopotential values. These results are in agreement with the observed fact that in Europe, winter predictions are generally more satisfactory than summer ones. A less obvious and somewhat speculative conjecture is to associate a cyclonic weather pattern over Western Europe to the North-Atlantic blocking: the high persistence of the latter appears as the consequence of the high predictability of the low-geopotential part of the attractor.

In a similarly detailed analysis, *Zeng et al.* (1992) utilized the time series of daily surface temperature and pressure over several regions of the United States and the North-Atlantic Ocean for estimating the predictability of the atmosphere. They also found that at least two Lyapunov exponents are positive with comparative magnitude. The main results can be summarized as follows. For sea-surface temperatures in the Atlantic, metric entropy $H = \Sigma\lambda_+$ varies between 0.094 and 0.148 day^{-1}, therefore t_e = 6.5–10.5 days; for sea-surface pressure data in the Atlantic, H varies between 0.101 and 0.142 day^{-1}, so that t_e = 7–10 days; for surface temperatures over the North-American continent,

$H = 0.186–0.276$ day^{-1}, $t_e = 3.5–5.5$ days; and for surface pressure over the North-American continent, $H = 0.402$ day^{-1}, $t_e = 2.5$ days; finally, a general conclusion: the predictability time in this region is larger in summer than in winter for all state variables. We can see that the time scales are smaller than those inferred by Keppenne and Nicolis. This discrepancy may be explained partly by the fact that t_e depends on how the magnitude of initial errors is defined in the different calculations (t_e is short for small initial errors and longer for larger initial errors), and partly by the fact that surface processes are less predictable than upper-air processes (see, e.g. *Yang*, 1991).

Among the specialized meteorological prediction problems, the forecasting of tropical cyclone tracks is generally identified as the one where obtaining a significant level of skill is very difficult. By applying nonlinear systems analysis methods to the evolution of tropical cyclone tracks in the Australian region, *Fraedrich* and *Leslie* (1989) found that the correlation dimensionality d_C of the system is between 6 and 8, and that the *e*-folding error growth time scale is about 24 hours. In the case of mid-latitude cyclones in the North Pacific region, t_e is between 4 and 7 days (*Fraedrich et al.*, 1990).

Predictability on climatic time scales. Much of our information on the evolution of the earth's climatic state during the past million years comes from the time series describing the isotope record of deep-sea cores. In their attractor reconstruction calculations, *Nicolis* and *Nicolis* (1984) used the oxygen isotope record obtained from the V-28-238 equatorial Pacific deep-sea core of N. J. Shackleton and N. D. Opdyke, and extended it over the past million years. They concluded in the existence of a low- (about three) dimensional attractor and a predictability time of about 30,000 years. Comparable results were obtained from the analysis by *Fraedrich* (1987), whose calculations were based on the oxygen isotope record gained from the *Meteor* 13519 deep-sea core in the eastern equatorial Atlantic, covering 775,000 years before present. Fraedrich's estimates have led to the existence of a climate attractor with the dimensionality $d_L = 4.4–4.8$, and a climate predictability time scale t_e = 10,000–15,000 years.

The occurrence of El Niño-Southern Oscillation (ENSO) episodes is highly irregular with time intervals between one and seven years. Therefore, it is not surprising that a similarity with a deterministic low-order chaotic system driven by the seasonal cycle has been suggested (see, e.g., *Göber et al.*, 1992; *Jin et al.*, 1994; *Tziperman et al.*, 1994). Nonlinear deterministic analysis of the annual time series of the ENSO carried out by *Fraedrich* (1988) has led to *e*-folding predictability time scales up to 1.5 years, indicating that at least a skillful nowcasting of ENSO may be possible. This conclusion is in agreement with numerical modelling results stating that ENSO is generally predictable one or two years ahead (*Brankovic et al.*, 1994).

Before closing this section, a short remark should be made concerning the reliability of the calculations aiming to reconstruct weather and climate attractors. The existence of low-dimensional attractors that was found in most of these attempts is currently a highly debated subject; for more details of this problem, the reader is referred to the article by *Götz* (1994).

5. Ensemble prediction

Since the notion of *predictability* is related to the rate of divergence of forecasts started from almost identical initial states, one potential method of estimating weather predictability is to construct an *ensemble* of possible initial states, each one being, *a priori*, equally likely. We can then integrate a deterministic numerical weather prediction model from each initial state, and produce an ensemble of forecasts for day 1, day 2 and so on. By studying the dispersion of the ensemble as the forecast proceeds, one can determine whether or not the uncertainties in the initial analyses were having a serious detrimental effect on forecast quality. Since each member of the ensemble is supposed to be equally likely, such a technique gives an essentially probabilistic forecast. In situations in which the ensemble of forecasts has a relative small dispersion, the predictability of the atmosphere is higher than average, and there is a high probability for some particular development. On the other hand, if initial uncertainties have amplified to such an extent that at a given forecast time the probabilities are spread more or less uniformly through a range of possible values then, for the particular state variable in question, the predictive skill has been lost (*Palmer et al.*, 1990).

The idea of ensemble forecasting was introduced in the context of numerical weather prediction by *Lorenz* (1965) and *Epstein* (1969). The technique was further developed by *Leith* (1974), who showed that if the uncertainties in the initial state are correctly specified, even with a relatively small ensemble size adequate accuracy can be obtained for the best mean of the forecast field. Their pioneering work has clearly revealed that the basic factors which determine the overall skill of an ensemble prediction are related to the questions of how large the size of an ensemble should be, and how best to generate the initial perturbations.

Probabilities based on very small initial sample sizes could be quite unrealistic. On the other hand, performing ensemble forecasts that have more than 100 members can be ruled out from practical considerations. Preliminary calculations suggest that there are about 50 important modes of instability for a realistic atmospheric flow. This number therefore represents approximately the ideal size of an ensemble, and may not be unreasonable from the point of view of development in computing technology as a result of the maturation of massively-parallel-processor architecture (*McPherson*, 1994).

Concerning the way in which the initial ensemble of states should be constructed, first we mention that, in some of the early attempts at producing an ensemble prediction, the simple technique of adding to a given analysis a spatially uncorrelated random (Monte Carlo) perturbation at each model grid point was used. However, if we integrate such perturbed analyses forward in time, the dispersion of the ensemble may start to decrease, since arbitrary random perturbations will mainly project onto non-meteorological modes (inertia-gravity waves), which are generally decaying in the model. In such a situation, the eventual delayed dispersion of the ensemble leads to an overestimate of the predictability. In order to overcome this problem, we must ensure that all members of the manifold lie on the attractor of the system or, in other words, that they belong to the atmospheric *slow manifold* which consists of the set of all meteorological modes. But there is an even more important constraint to fix the initial ensemble, imposed by the dynamical instability properties of the basic flow. Uncertainties in the initial conditions are most important in regions where the flow is dynamically (baroclinically and/or barotropically) unstable. We therefore need to perturb the initial data in these regions, and with such a vertical and horizontal structure that will most readily excite the appropriate unstable normal modes. However, as we have seen, the normal-mode instabilities are by no means the fastest-growing (highest-energy) perturbations over periods of time relevant for short- and medium-range prediction: integrations up to 15 days have revealed that the growth rates of perturbations that are not of normal-mode form can be up to an order of magnitude larger than the most unstable normal-mode instability. These perturbations are often referred to as the *optimally growing errors*; their amplitudes can double in less than 12 hours and grow as much as 10-fold (energy as much as 100-fold) over 36 hours (*Molteni* and *Palmer*, 1993; *Buizza* and *Palmer*, 1994).

It is beyond the scope of this article to give details on the techniques that have recently been developed to calculate the optimally growing modes of instability of a given basic flow for the construction of the initial ensemble. In short, up to now two methods have been explicitly designed to generate efficient initial perturbations for ensemble forecasting. The 'optimal method', adopted at the European Centre for Medium-range Weather Forecasts (ECMWF), is based on a direct computation of the singular vectors of the tangent linear equations. The initial perturbations are constructed from 16 of the dominant singular vectors associated with the 36-hour *forecast* trajectory (*Palmer et al.*, 1992, 1994; *Buizza et al.*, 1993; *Mureau et al.*, 1993). The other method, developed at the U.S. National Meteorological Center (NMC), estimates the perturbations that *were* growing fastest during the 6-hour interval leading to the initial time t_0 by having introduced a small arbitrary perturbation on the control analysis at time $t_0 - 6$ hours. At time t_0, the difference between the control and perturbed forecasts is scaled back to the size of the original perturbation (a necessary step to keep the amplitude limited, since a *nonlinear* model is used), and this difference field is then added to the new analysis. As the process is repeated forward in time, the scheme selects ('breeds') the modes that grow fastest during the cycle, and therefore this method has been denoted *breeding of the growing modes* (*Tracton* and *Kalnay*, 1993; *Toth* and *Kalnay*, 1993). For a sufficiently long period of time (about three days for the baroclinic atmosphere), these efficient perturbations asymptote to the local Lyapunov vectors in the phase space of the system. The conjecture of the method is that these are the well-organized perturbations present in the analysis cycle, leading to fast short-range forecast error growth.

A comparative verification of the two methods is not yet available. The ECMWF approach may be optimal in detecting the maximum range of possible forecast errors, while the NMC method may give a better estimate of the errors in the initial analysis.

Finally, for the sake of clarity, it might be important to emphasize that an uncertainty in the initial analysis is by no means the single source of forecast errors; incomplete model physics can, of course, also generate erroneous predictions. We know that the construction of a physically perfect model is probably quite as much an impossibility as the specification of perfect initial conditions. Yet, one of the most fundamental assumptions of the ensemble forecasting techniques is the *perfect-model hypothesis*. The reason of the necessity to introduce such an assumption is that if the numerical weather prediction model was not perfect, the control forecast and the model-generated unstable perturbations would characterize the stability conditions of the model itself, rather than those of the real atmosphere. Model-verification experiments have clearly revealed that, at least on global scales and on time scales of medium-range forecasts, the perfect-model hypothesis is satisfied in most of the synoptic situations in such a form that forecast errors arising from incomplete initial conditions are considerably larger than those resulting from model-physics deficiencies.

6. Concluding remarks

The mathematical equations governing the dynamics of the atmospheric flow are nonlinear, and the observed structure of the atmosphere is characterized by horizontal and vertical gradients of air motion, temperature and humidity that permit hydrodynamical and thermodynamical instabilities to develop. Inevitable uncertainties in the initial state can grow due to the inherent instability of the flow and nonlinear interactions among motions of different space and time scales, placing a fundamental upper limit on the deterministic predictability of atmospheric behaviour.

Recent developments of the theory of dynamical systems have provided new techniques by which important information can be obtained concerning the extent of predictability of the system's evolution, independent of any modelling.

The predictability of a dynamical system is determined by the divergence of phase-space trajectory segments whose starting points are close. For chaotic systems, initially nearby trajectories diverge asymptotically at an exponential rate given by the positive Lyapunov exponents. These exponents are evaluated in the limit $t \to \infty$, and characterize many of the *global* (phase-space) properties of the associated attractor. However, the degree of divergence of *finite* segments of the trajectory depends strongly on the position of the starting points in the attractor set. Moreover, finite-time divergence rates need not be exponential, and can be much larger than those given by the Lyapunov exponents. Therefore, Lyapunov exponents are of limited use for studies of the *local* predictability properties of the system's attractor, that is of the dependence of perturbation growth on initial state. In recent years, much effort has been devoted to find the so-called *optimal excitation*, i.e. the perturbation that grows fastest on time scales of interest in numerical prediction.

The inherent deterministic forecasting limitation in nonlinear fluid-flow problems has motivated to try alternative approaches, like stochastic-dynamic modelling, statistical techniques and ensemble prediction. The ensemble technique reflects explicitly the recognition that the atmosphere is a chaotic system: here, a nonlinear deterministic numerical forecast is made several times from a set of perturbed initial states, each of which is, in principle, consistent with the available data. The choice of initial perturbation is guided by recent theoretical developments: a selection of the fastest-growing errors are used. By exciting the most energetically growing disturbances in the linear error-growth range, model-generated ensemble dispersion is then taken to be a measure of predictability.

The very existence of intrinsically imposed limits of predictability will undoubtedly have a lasting effect on the way to model or even monitor the environment. On the other hand, the average predictability times found for the evolution of the atmosphere on different time scales suggest that there is considerable room for improving forecast techniques for phenomena belonging to the relevant time scale.

Acknowledgements—The author is most grateful to the two anonymous reviewers, who made some particularly useful comments and suggestions to improve the original manuscript.

References

Abarbanel, H.D.I., Brown, R. and *Kennel, M.B.*, 1991: Variations of Lyapunov exponents on a strange attractor. *J. Nonlinear Sci. 1*, 175-199.

Benzi, R. and *Carnevale, G.F.*, 1989: A possible measure of local predictability. *J. Atmos. Sci. 46*, 3595-3598.

Bergeron, T., 1959: Methods in scientific weather analysis and forecasting. In *The Atmosphere and the Sea in Motion* (ed.: *B. Bolin*). The Rockefeller Institute Press and Oxford University Press, New York, pp. 440-474.

Bjerknes, V., 1904: Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik. *Meteor. Zeitschrift 21*, 1-7.

Borges, M.D. and *Hartmann, D.L.*, 1992: Barotropic instability and optimal perturbations of observed zonal flows. *J. Atmos. Sci. 49*, 335-354.

Brankovic, C., *Palmer, T.N.* and *Ferranti, L.*, 1994: Predictability of seasonal atmospheric variations. *J. Climate 7*, 217-237.

Buizza, R. and *Palmer, T.N.*, 1994: The singular vector structure of the general circulation. In *Research Activities in Atmospheric and Oceanic Modelling*, Report No. 19 (ed.: *G.J. Boer*). WMO/TD-No. 592, pp. 2.10-2.11.

Buizza, R., *Tribbia, J.*, *Molteni, F.* and *Palmer, T.*, 1993: Computation of optimal unstable structures for a numerical weather prediction model. *Tellus 45A*, 388-407.

Charney, J.G., 1951: Dynamic forecasting by numerical process. In *Compendium of Meteorology* (ed.: *T.F. Malone*). American Meteorological Society, Boston, pp. 470-482.

Charney, J.G. and *DeVore, J.G.*, 1979: Multiple flow equilibria in the atmosphere and blocking. *J. Atmos. Sci. 36*, 1205-1216.

Charney, J.G., *Fjörtoft, R.* and *von Neumann, J.*, 1950: Numerical integration of the barotropic vorticity equation. *Tellus 2*, 237-254.

Epstein, E.S., 1969: Stochastic dynamic prediction. *Tellus 21*, 739-759.

Farmer, J.D., *Ott, E.* and *Yorke, J.A.*, 1983: The dimension of chaotic attractors. *Physica 7D*, 153-180.

Farmer, J.D. and *Sidorowich, J.J.*, 1987: Predicting chaotic time series. *Phys. Rev. Lett. 59*, 845-848.

Farrell, B., 1988: Optimal excitation of neutral Rossby waves. *J. Atmos. Sci. 45*, 163-172.

Farrell, B.F., 1989: Optimal excitation of baroclinic waves. *J. Atmos. Sci. 46*, 1193-1206.

Farrell, B.F., 1990: Small error dynamics and the predictability of atmospheric flows. *J. Atmos. Sci. 47*, 2409-2416.

Fraedrich, K., 1987: Estimating weather and climate predictability on attractors. *J. Atmos. Sci. 44*, 722-728.

Fraedrich, K., 1988: El Niño/Southern Oscillation predictability. *Mon. Wea. Rev. 116*, 1001-1012.

Fraedrich, K., *Grotjahn, R.* and *Leslie, L.M.*, 1990: Estimates of cyclone track predictability. II: Fractal analysis of mid-latitude cyclones. *Quart. J. Roy. Meteor. Soc. 116*, 317-335.

Fraedrich, K. and *Leslie, L.M.*: 1989: Estimates of cyclone track predictability. I: Tropical cyclones in the Australian region. *Quart. J. Roy. Meteor. Soc. 115*, 79-92.

Göber, M., *Herzel, H.* and *Graf, H.-F.*, 1992: Dimension analysis of El Niño/Southern Oscillation time series. *Ann. Geophys. 10*, 729-734.

Götz, G., 1994: Application of nonlinear dynamics in atmospheric sciences. Part II. Some examples. *Időjárás 98*, 65-86.

Grassberger, P. and *Procaccia, I.*, 1983: Characterization of strange attractors. *Phys. Rev. Lett. 50*, 346-349.

Henderson, H.W. and *Wells, R.*, 1988: Obtaining attractor dimensions from meteorological time series. In *Advances in Geophysics*, Vol. 30 (ed.: *B. Saltzman*). Academic Press, San Diego, pp. 205-237.

Hirsch, M.W. and *Smale, S.*, 1974: *Differential Equations, Dynamical Systems, and Linear Algebra.* Academic Press, New York, 358 pp.

Jin, F.-F., *Neelin, J.D.* and *Ghil, M.*, 1994: El Niño on the devil's staircase: Annual subharmonic steps to chaos. *Science 264*, 70-72.

Kaplan, J.L. and *Yorke, J.A.*, 1979: Chaotic behavior of multidimensional difference equations. In *Functional Differential Equations and the Approximation of Fixed Points* (eds.: *H.O. Peitgen* and *H.O. Walther*). Springer Lecture Notes in Mathematics, Vol. 730. Springer-Verlag, Berlin, pp. 228-237.

Keppenne, C.L. and *Nicolis, C.*, 1989: Global properties and local structure of the weather attractor over Western Europe. *J. Atmos. Sci. 46*, 2356-2370.

Lacarra, J.-F. and *Talagrand, O.*, 1988: Short-range evolution of small perturbations in a barotropic model. *Tellus 40A*, 81-95.

Legras, B. and *Ghil, M.*, 1985: Persistent anomalies, blocking and variations in atmospheric predictability. *J. Atmos. Sci. 42*, 433-471.

Leith, C.E., 1974: Theoretical skill of Monte Carlo forecasts. *Mon. Wea. Rev. 102*, 409-418.

Lorenz, E.N., 1963: Deterministic nonperiodic flow. *J. Atmos. Sci. 20*, 130-141.

Lorenz, E.N., 1965: A study of the predictability of a 28-variable atmospheric model. *Tellus 17*, 321-333.

Lorenz, E.N., 1969: Atmospheric predictability as revealed by naturally occurring analogues. *J. Atmos. Sci. 26*, 636-646.

Lorenz, E.N., 1984a: The local structure of a chaotic attractor in four dimensions. *Physica 13D*, 90-104.

Lorenz, E.N., 1984b: Irregularity: A fundamental property of the atmosphere. *Tellus 36A*, 98-110.

McPherson, R.D., 1994: Advances in operational numerical weather prediction: An outlook for the early twenty-first century. In *Lectures Presented at the Forty-fifth Session of the WMO Executive Council*. WMO-No. 805, pp. 7-12.

Molteni, F. and *Palmer, T.N.*, 1993: Predictability and finite-time instability of the northern winter circulation. *Quart. J. Roy. Meteor. Soc. 119*, 269-298.

Mukougawa, H., *Kimoto, M.* and *Yoden, S.*, 1991: A relationship between local error growth and quasi-stationary states: Case study in the Lorenz system. *J. Atmos. Sci. 48*, 1231-1237.

Mureau, R., *Molteni, F.* and *Palmer, T.N.*, 1993: Ensemble prediction using dynamically conditioned perturbations. *Quart. J. Roy. Meteor. Soc. 119*, 299-323.

Nese, J.M., 1989: Quantifying local predictability in phase space. *Physica D 35*, 237-250.

Nese, J.M. and *Dutton, J.A.*, 1993: Quantifying predictability variations in a low-order ocean-atmosphere model: A dynamical systems approach. *J. Climate 6*, 185-204.

Nese, J.M., *Dutton, J.A.* and *Wells, R.*, 1987: Calculated attractor dimensions for low-order spectral models. *J. Atmos. Sci. 44*, 1950-1972.

Nicolis, C., 1992: Probabilistic aspects of error growth in atmospheric dynamics. *Quart. J. Roy. Meteor. Soc. 118*, 553-568.

Nicolis, C. and *Nicolis, G.*, 1984: Is there a climatic attractor? *Nature 311*, 529-532.

Nicolis, C. and *Nicolis, G.*, 1991: Dynamics of error growth in unstable systems. *Phys. Rev. A43*, 5720-5723.

Nicolis, C. and *Nicolis, G.*, 1993: Finite time behavior of small errors in deterministic chaos and Lyapunov exponents. *Int. J. Bifurcation and Chaos 3*, 1339-1342.

Oseledec, V.I., 1968: A multiplicative ergodic theorem. Lyapunov characteristic numbers for dynamical systems. *Trans. Moscow Math. Soc. 19*, 197-231.

Ott, E., 1993: *Chaos in Dynamical Systems*. Cambridge University Press, Cambridge, 385 pp.

Packard, N.H., *Crutchfield, J.P.*, *Farmer, J.D.* and *Shaw, R.S.*, 1980: Geometry from a time series. *Phys. Rev. Lett. 45*, 712-716.

Palmer, T.N., 1993: Extended-range atmospheric prediction and the Lorenz model. *Bull. Amer. Meteor. Soc. 74*, 49-65.

Palmer, T.N., *Buizza, R.*, *Molteni, F.* and *Mureau, R.*, 1994: The ECMWF ensemble prediction system. In *Research Activities in Atmospheric and Oceanic Modelling*, Report No. 19 (ed.: *G.J. Boer*). WMO/TD-No. 592, pp. 6.17-6.18.

Palmer, T., *Molteni, F.*, *Mureau, R.*, *Buizza, R.*, *Chapelet, P.* and *Tribbia, J.*, 1992: *Ensemble Prediction*. ECMWF Research Department Tech. Memo. No. 188.

Palmer, T.N., *Mureau, R.* and *Molteni, F.*, 1990: The Monte Carlo forecast. *Weather 45*, 198-207.

Parker, T.S. and *Chua, L.O.*, 1987: Chaos: A tutorial for engineers. *Proc. IEEE 75*, 982-1008.

Reinhold, B.B. and *Pierrehumbert, R.T.*, 1982: Dynamics of weather regimes: Quasi stationary waves and blocking. *Mon. Wea. Rev. 110*, 1105-1145.

Richardson, L.F., 1922: *Weather Prediction by Numerical Process*. Cambridge University Press, Cambridge, 236 pp.

Ruelle, D., 1981: Chemical kinetics and differentiable dynamical systems. In *Nonlinear Phenomena in Chemical Dynamics* (eds.: *A. Pacault* and *C. Vidal*). Springer-Verlag, Berlin, pp. 30-37.

Ruelle, D., 1989: *Chaotic Evolution and Strange Attractors*. Cambridge University Press, New York.

Shukla, J., 1985: Predictability. In *Advances in Geophysics*, Vol. 28B: Weather Dynamics (ed.: *S. Manabe*). Academic Press, Orlando, pp. 87-122.

Takens, F., 1981: Detecting strange attractors in turbulence. In *Dynamical Systems and Turbulence* (eds.: *D.A. Rand* and *L.-S. Young*). Warwick 1980 Lecture Notes in Mathematics, Vol. 898. Springer-Verlag, Berlin, pp. 366-381.

Thompson, P.D., 1957: Uncertainty of initial state as a factor in the predictability of large scale atmospheric flow patterns. *Tellus 9*, 275-295.

Toth, Z. and *Kalnay, E.*, 1993: Ensemble forecasting at NMC: The generation of perturbations. *Bull. Amer. Meteor. Soc. 74*, 2317-2330.

Tracton, M.S. and *Kalnay, E.*, 1993: Operational ensemble prediction at the National Meteorological Center: Practical aspects. *Wea. Forecasting 8*, 379-398.

Trevisan, A., 1993: Impact of transient error growth on global average predictability measures. *J. Atmos. Sci. 50*, 1016-1028.

Tribbia, J.J. and *Baumhefner, D.P.*, 1988: Estimates of the predictability of low-frequency variability with a spectral general circulation model. *J. Atmos. Sci. 45*, 2306-2317.

Tziperman, E., Stone, L., Cane, M.A. and *Jarosh, H.*, 1994: El Niño chaos: Overlapping of resonances between the seasonal cycle and the Pacific ocean-atmosphere oscillator. *Science 264*, 72-74.

Vannitsem, S. and *Nicolis, C.*, 1994: Predictability experiments on a simplified thermal convection model: The role of spatial scales. *J. Geophys. Res. 99*, 10,377-10,385.

Vukicevic, T., 1991: Nonlinear and linear evolution of initial forecast errors. *Mon. Wea. Rev. 119*, 1602-1611.

Yang, P., 1991: On the chaotic behavior and predictability of the real atmosphere. *Adv. Atmos. Sci. 8*, 407-420.

Zeng, X., 1992: *Chaos Theory and Its Application in the Atmosphere*. Department of Atmospheric Science, Colorado State University, Atmospheric Science Paper No. 504.

Zeng, X., Pielke, R.A. and *Eykholt, R.*, 1992: Estimating the fractal dimension and the predictability of the atmosphere. *J. Atmos. Sci. 49*, 649-659.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 1, January-March 1995

Problems in lysimeter use for determining the water demand of sugar beet

Angéla Anda

Pannon Agricultural University,
P.O. Box 71, H-8361 Keszthely, Hungary

(Manuscript received 5 January 1995; in final form 15 March 1995)

Abstract—Investigation on evapotranspiration and changes in plant features as assimilatory surface, stomatal resistance, soil temperature and plant production of three different sugar beet varieties grown at non-limited water supply in Thornthwaite type compensation evapotranspirometers (or lysimeters) were carried out at Keszthely, Hungary, during the 1992 growing season. (The surface area of soil containers of the evapotranspirometers was 4 m^2, the depth of them was 1 m.) Already in the early stage of plant development it became evident, that the water supply and the ratio of soil moisture and soil air in the containers of lysimeters were not advantageous for sugar beet growing (size and color of leaves). The assimilatory surface of plants grown in lysimeters decreased significantly, and caused differences also in parameters of microclimate (soil and air temperatures, relative humidity of air) and other plant characteristics as compared to the control treatment. The LAI in the irrigated treatments decreased considerably, and caused increase in soil surface temperatures. The higher the soil temperature, the larger the stomatal resistance was experienced in watered canopies. These symptoms were completely contrary to our expectations. The direction of change in plant characteristics of irrigated treatments has a negative influence on plant sugar production, where the yield depressions were between 3.2 and 40.9% depending on crop variety.

There was significant difference in measured plant and microclimatic parameters of the three cultivars as well. In spite of higher soil moisture of lysimeters there was a strong decrease in sugar production of *Gála* and *Kawemaya* varieties. Either studied crop parameters or production of watered *Éva* cultivar has changed on the least extent as compared to the control ones, that means different sensitivity of the three sugar beet varieties for altered environmental (soil water) conditions. The change in soil air-water ratio resulted from continuous water supply in the lysimeter soil had negative effect on production of two beet cultivars. To determine the sugar beet water demand correctly, other water supply methods of containers or deeper lysimeter tanks would be necessary.

Key-words: sugar beet, evapotranspiration, yield and quality, soil temperature, stomatal resistance, LAI, sugar beet varieties.

1. Introduction

The main characteristic of the climate of Hungary is the tendency for dryness and frequent drought. To cope with shortage of rainfall irrigation is needed. To plan irrigation correctly, both plant water demand and precipitation should be followed during the whole vegetative period. To measure the amount of rainfall is out of problem, but the exact determination of evapotranspiration of plant stands involves both technical and theoretical difficulties. One of the instruments fulfilling the purpose of following plant water losses is the lysimeter or evapotranspirometer. In the frame of Hungarian Meteorological Service investigations on lysimeter use for plant water demand measurements has been carried out from the early 60-es (*Antal* 1966a, 1966b; *Antal* and *Posza*, 1967). Further on these investigations *Antal* (1968a, 1968b) developed his method to estimate the evapotranspiration of different plant stands.

In the first decade of investigations meteorological and agricultural researchers have studied variation in water loss of arable crops (*Antal,* 1966a, 1972; *Antal* and *Posza*, 1967, 1970; *Petrasovits,* 1970; *Antal* and *Endrődi*, 1972; *Erdős,* 1966; *Szlovák,* 1979; *Fekete* and *Szilágyi*, 1979; *Endrődi,* 1979; *Kádár* and *Szilágyi*, 1980), then the evapotranspiration investigations were concentrated to vegetable plants, fruit trees and vineyard (*Kozma* and *Füri*, 1974; *Stollár* and *Gergely*, 1978; *Novák* and *Szilágyi*, 1980; *Posza,* 1980; *Cselőtei,* 1991; *et al.*). From second decade of experiments the evapotranspiration studies were applied to explain other environmental (agricultural) phenomena such as for example water balance changes resulting from using different amounts of artificial fertilizers (*Antal et al.*, 1975; *Tóth*, 1978; *Ruzsányi,* 1975, 1981), plant densities (*Walkowszki,* 1978), or effect of soil water table (*Szalóki,* 1971; *Posza,* 1978).

As there were merely publications in Hungary on changes in microclimatic and some of the plant characteristics of sugar beet when growing them in lysimeters, the goal of our experiment was to measure a few water balance components together with alteration of microclimate, and plant elements of three different sugar beet varieties grown at non-limited water supply in lysimeter containers. Parallel evapotranspiration investigations other plant features as leaf area, stomatal resistance and production of sugar beet were also studied. Detailed investigations on determining sugar beet water consumption by using lysimeter measurements has been carried out under Hungarian climatic conditions earlier by *Antal* and *Posza* (1970), *Endrődi* (1973, 1974), and *Ruzsányi* (1990).

2. Material and methods

Investigations were carried out on sugar beet grown in Thornthwaite type compensation evapotranspirometers at Keszthely Agrometeorological Research Station, Hungary, during the 1992 growing season. Three sugar beet varieties

(*Kawemaya* — widely used in Europe, bred in Germany, *Gála* and *Éva* — two Hungarian varieties) were sown into lysimeter-soil containers (tanks) filled with Ramann type brown forest soil. The soil surface area of tanks 4 m^2 and the depth of them 1 m. Plant density was among 10 to 12 per m^2. Daily sum of evapotranspiration was calculated by following the water balance components of plant stands by using the original method of *Antal* (1968b). The comparison of evapotranspiration of different beet varieties was made with the help of calculated pentad means of water losses and by using transpiration intensity per unit leaf area.

Simultaneously with lysimeter measurements, the above mentioned three sugar beet cultivars were grown at natural rainfall only (control). Both the sizes of control plots and plant density were the same as used in lysimeter tanks. Altogether we had 6 treatments: 3 beet cultivars grown in lysimeters and the same 3 under natural rainfall only. The number of replications was 4.

Leaf area of sugar beet crops was measured on 5 plants in each of the treatments by LI-3000 type portable planimeter in every two weeks. The size of assimilatory surface was explained with leaf-area-index (LAI).

Stomatal resistance was determined by LI-60 type diffusive porometer on 3 to 5 sunlit upper leaves on 5 days with completely clear sky conditions hourly between 8 to 17 h with the aim of getting comparable results the age of leaf, place of measurement on blades (upper third of leaf from the stem) and orientations of sample leaves were more or less the same.

Because of well-known heterogeneity of soil structure and temperature, instead of point measurements by using traditional mercury thermometers, a new method was introduced to determine the actual plot-soil surface temperature (*Anda,* 1993). A Raynger II.RTL type infrared thermometer was applied to determine soil surface temperature on the same 5 days of the growing season when stomatal resistance was also measured. Diurnal variation of soil temperature was characterized by representing the hourly values each sample day.

In the end of the vegetation period sugar yield per unit soil area was determined by measuring both the root yield and sugar content of roots.

As there was no significant difference in plant- and other characteristics between irrigated and non-irrigated treatments of *Éva* cultivar, mainly the results of the other two varieties will be represented. When it is necessary, measurements for *Éva* will also be shown and analyzed.

3. Results and discussion

3.1 Assimilatory surface

The change in architecture of plant stand has of primary importance in plant studies, because they influence distribution of other crop- and microclimatic parameters determining plant production. In our study architecture of plant stands was therefore characterized by leaf-area-index.

The green leaf size among both three cultivars and irrigated and control treatments differed significantly during the 1992 growing season, mainly after the canopy closure. In lysimeters *Éva* had by 27.6 percent higher LAI than that of the assimilatory surfaces of *Kawemaya*, the variety of the smallest leaf area. The LAI values of *Gála* were between the other two cultivars. In control canopies the order of assimilatory surface size of different sugar beet varieties was completely different: the *Kawemaya* had the largest LAI, and the decreases in annual LAI mean of *Gála* and *Éva* was 11.7 and 33.8 percent respectively, as compared to the LAI values of *Kawemaya*.

In contrary with our expectations, the continuous high soil moisture content in the lysimeter tanks resulted in a decrease of yearly LAI averages in *Kawemaya* and *Gála* by 65 and 34 percent respectively, comparing to the LAI of non-irrigated control varieties *(Fig. 1)*. The time of developing maximum green leaf area appeared two weeks earlier in growing tanks of lysimeter considering *Kawemaya* and *Gála* varieties. As it was mentioned in Introduction chapter, either the LAI or its maximum value has not changed significantly in variety *Éva* as a result of increased soil moisture content.

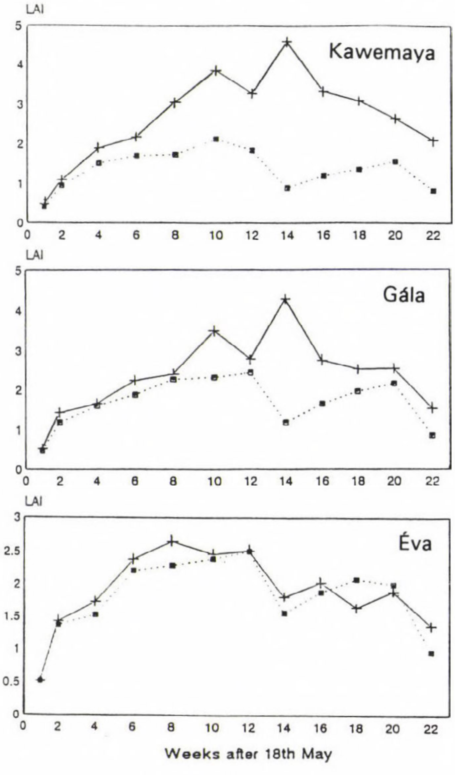


Fig. 1. Leaf area index of different sugar beet varieties.

The sensitivity of three different beet cultivars for increased soil moisture content was not the same. Variety *Éva* of least green leaf size and production showed the fewest sensitivities for continuous high soil water level (0.9 m from the soil surface in 1 m deep lysimeter tanks). The other two sugar beet varieties, the *Kawemaya* and *Gála* of increased assimilatory surface and yield were hypersensitive to changed soil water and air ratio. Unhealthy colored yellow plants in lysimeter tanks with decreased assimilatory leaf surface showed that there is a water supply problem when the sugar beet grows in relatively shallow evapotranspirometer tanks. Probably there was an out of air shortage problem in the root zone of the compensation lysimeter during the dry and warm growing season of 1992. The similar symptom was experienced by *Endrődi* (1973, 1974).

3.2 Plant water balance components

Growing season of 1992 was drier and warmer than in usual, especially in the second half of investigation period (from the end of July to the end of August), when the daily sum of potential evapotranspiration frequently reached the 7–8 mm, and never decreased below 4 mm. Until the end of August the daily mean of air temperature values often approached to 25°C measured at the Agrometeorological Research Station of Keszthely. Sum of precipitation during July and August was altogether 58 mm only. The ratio of precipitation and potential evapotranspiration was 68.3 percent for the whole growing season of 1992, meaning a dry and warm vegetation period during 1992.

There were no significant differences in the summarized evapotranspiration sums among the three sugar beet varieties grown in evapotranspirometers. Like a tendency, the water loss of *Éva* increased by 3.5 percent, comparing to the evapotranspiration of the other two varieties. Oppositely to summarized water consumption, the transpiration intensity in the different treatments has changed significantly *(Fig. 2)*. The variety of *Kawemaya* had the highest (evapo)transpiration intensity of all. Decrease in annual average of transpiration rate of the other two cultivars were 17.4 and 24.3 percent in *Gála* and *Éva* plant stands, respectively. The cause of increased water loss of *Kawemaya* might have been associated with change in microclimatic conditions resulting from altered assimilatory surface of irrigated plants. The soil surface temperature measurements seemed to justify this assumption during 1992.

3.3 Soil surface temperatures

The likely reason of increased transpiration intensity of *Kawemaya* might have been associated with decreased size of shadowing leaf area causing higher soil heat accumulation. The higher the soil temperature, the larger the transpiration was in irrigated treatments. In this experiment the change in soil surface temperature resulting from alteration in shadowing leaf area was much higher when comparing the irrigated and non-irrigated treatments *(Fig. 3a)*. Difference in annual average of the soil temperature between watered and control plants was 2.8 and 2.4°C in *Kawemaya* and *Gála* canopies, respectively. The time of appearing of highest temperature changes occurred in the afternoon hours *(Fig. 4)*, when the soil temperature of lysimeters was sometimes 3 to 5°C warmer, than that of the controls. Independently, on both beet cultivars and assimilatory surface size in the morning hours an opposite tendency occurred, and the soil surface temperature in the control treatments was about 0.5 to 1°C warmer than the temperature of lysimeters in the top soil. The likely reason might have been associated with water-filling up of upper soil layer of evapotranspirometer tanks, during the night, when there was enough time for capillarity to reach the top soil also. This water evaporates easily in the early morning and cools the soil surface temperature in the evapotranspirometer tanks. Later, with higher insolation and soil warming, there is not enough time to filling up with water, and the subsoil irrigation water originating from the bottom of lysimeter tanks can not compensate the increasing rate of evaporation. After 10–11 h, the size of assimilatory surface plays leading role in determination of actual soil surface temperatures.

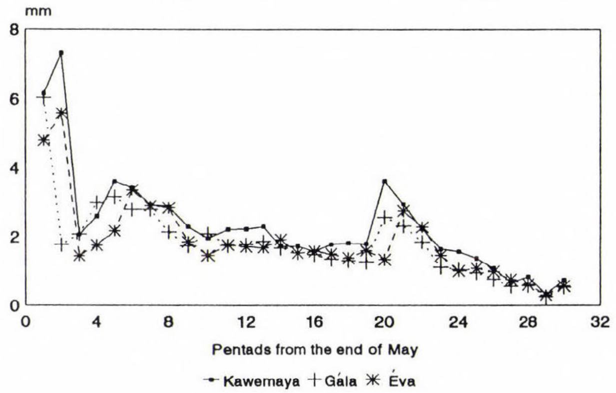


Fig. 2. Intensity of evapotranspiration in sugar beet in Keszthely, 1992.

The change in soil heat accumulation of watered canopies caused other differences in parameters of microclimate. The higher the soil temperature in lysimeters, the warmer and drier the air was at about 1 m above the plant stand. Size of change resulting from altered plant growing conditions depended on time of day. At low sun radiation there was no difference in measured micro-meteorological elements. At high radiation level the air about 1 m above irrigated crops was 1.5 to 2.5°C warmer and 10 to 15 percent richer in relative

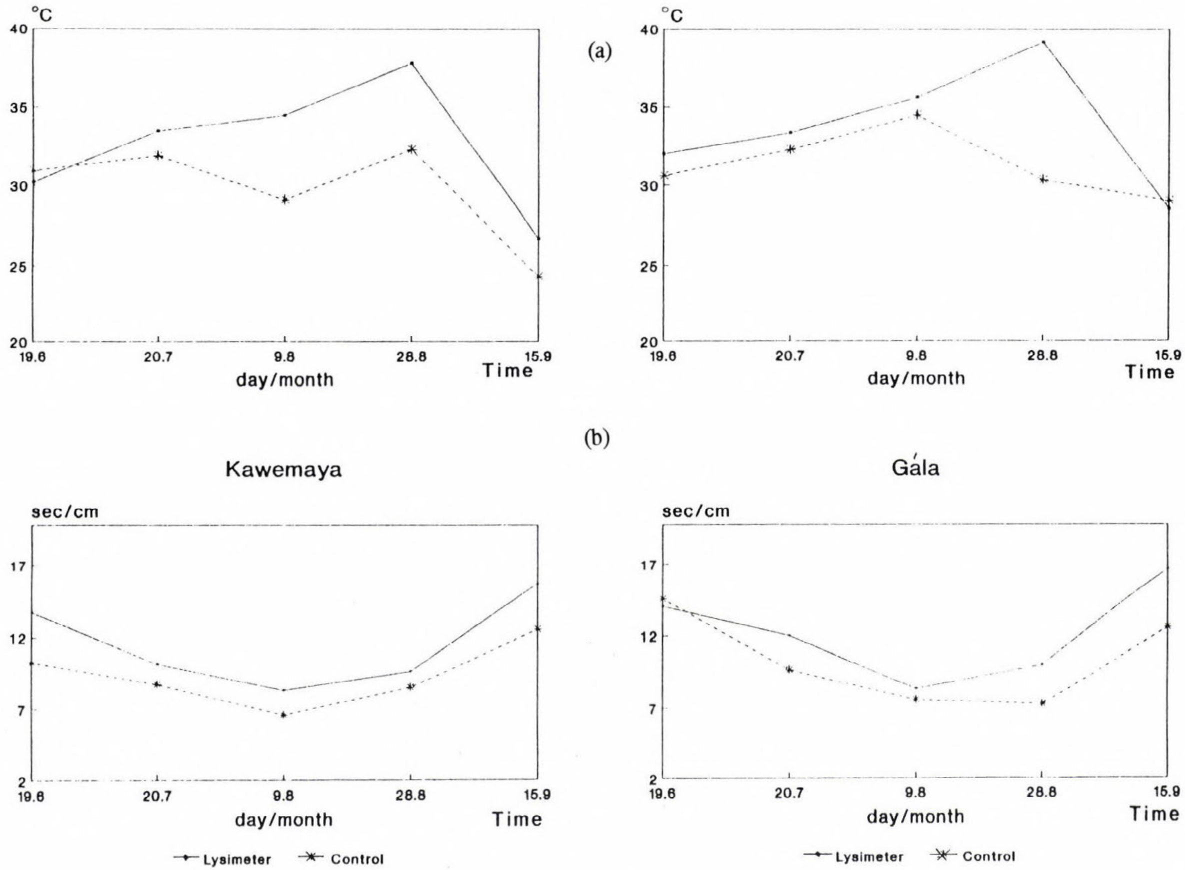


Fig. 3. Annual changes in soil surface temperature (*a*) and stomatal resistance (*b*).

humidity content than the air of control plant stands. Because of LAI depression and soil temperature increase at watered canopies, in contrary with expectations, the irrigated canopies had warmer and drier microclimate.

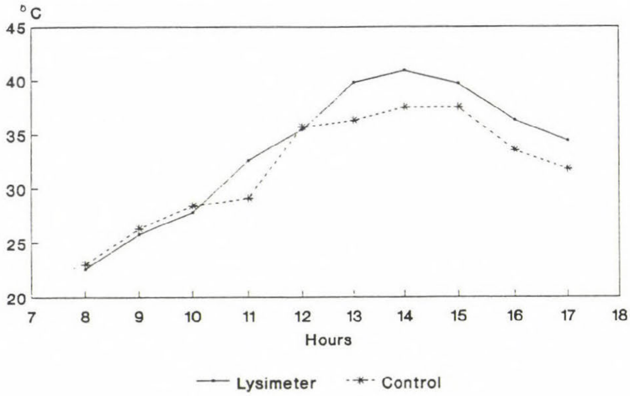


Fig. 4. Diurnal variation of soil temperature in *Kawemaya* on 19th July, 1992.

3.4 Stomatal resistance

Alterations in stomatal resistance of different varieties were in accordance with soil temperature and microclimatic changes. Analyzing the relationship between the soil surface temperature and the stomatal resistance a linear relationship was determined. The increase in 1 °C of soil temperature caused a 0.7 sec/cm decrease in stomatal resistance during the measuring period of 1992 independently of water supply. In *Kawemaya's* canopy both the soil and air temperature values were the highest and the average stomatal resistances were the lowest of all. The low stomatal resistance means of largest pore-apertures caused the highest transpiration intensity of *Kawemaya* canopy. The increase in annual mean resistance of *Gála* and *Éva* was 5.9 and 29.6 percent, respectively.

Stomatal resistance determined in control canopies showed strong decrease comparing to the resistance of plants grown in lysimeter-container *(Fig. 3b)*. The measures of change in annual means were 20.9 and 16.9 percent in *Kawemaya* and *Gála,* respectively. There was only one exception, the variety *Éva,* where the subsoil irrigation did not cause significant difference in diffusion resistances. Like a tendency, the largest changes in resistance of plants grown in lysimeter appeared in the afternoon hours *(Fig. 5)*. As there was no difference in diurnal course of resistances between the varieties, the results determined in *Kawemaya* canopy will be shown only. The influence of irrigation on stomatal resistance occurred mainly in the afternoon hours. The irrigated sugar beet crops' behavior was completely opposite to the measured resistances of watered plants by *Lawlor* and *Milford* (1975) and *Huzulak* and *Matejka* (1992). It is important to mention that these investigators used surface irrigation method and not lysimeters with subsurface irrigation. Increase in resistance of lysimeter's plants showed other than water shortage problem when sugar beet is grown in 1 m deep lysimeter tanks. At first, decreased and yellow colored leaves made us think shortage of minerals, mainly lack of nitrogen. Partial leaf-analysis refuted this assumption. The real cause might have been shortage of air in soil of lysimeter-containers resulted from continuous high soil water level. It seems, that the sugar beet is more sensitive to proper soil air-water ratio than that of the other earlier grown plants in lysimeter.

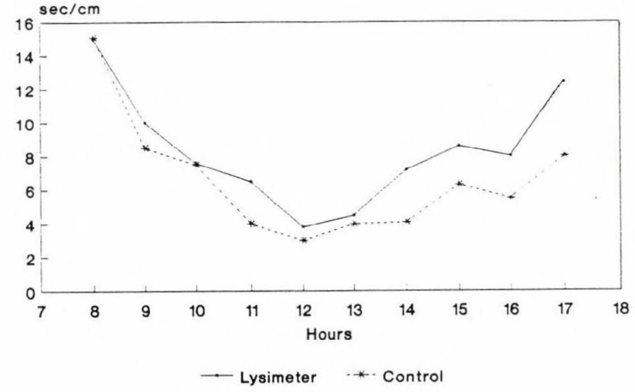


Fig. 5. Diurnal course of stomatal resistance in *Kawemaya* on 9th August 1992.

3.5 Plant production

Similarly to summarized evapotranspiration, there was no significant difference in sugar production per unit soil area of three beet varieties at non-limited water supply. The excess water equalized the productivity of different cultivars, while unfavorable air-water conditions of lysimeter soil caused in 45.9 and 33.3 percent sugar yield decrease of *Kawemaya* and *Gála*'s treatment, respectively *(Fig. 6)*. The variety *Éva* produced the least and not significant yield depression to changed soil air-water ratio of all (3.2 percent).

The higher the produced sugar yield, the better the sugar beet variety was, when growing them without irrigation. In our experiment the above mentioned fact may be substituted with the following: the better the sugar beet cultivar at limited water supply, the more sensitive is, when growing them in shallow lysimeter's container. At control, the *Kawemaya* was the best yielded variety of all. The yield depressions of *Gála* and *Éva* were 5.9 and 40.3 percent, as compared to the production of *Kawemaya* at natural rainfall. In our one year experiment, the variety of high-production property was more sensitive to proper environmental and growing conditions, among others for optimal air-water ratio in the soil than that of the other beet canopies. The best yielded variety, the *Kawemaya* may be grown on well aerated 'easy' soil types mainly. Change in sugar production of *Éva* (variety with least productivity at control condition) was negligible when changing the proper environmental conditions for growing sugar beet. It is the task of plant growers to reconcile the environmental condition of their growing area with the necessity of different sugar beet varieties of changed sensitivity.

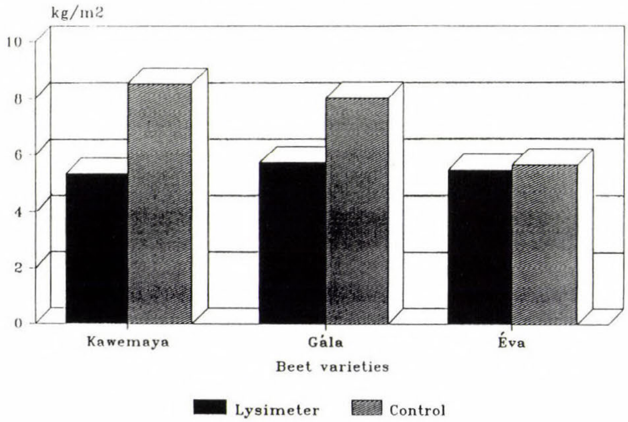


Fig. 6. Sugar production of different varieties.

References

Anda, A., 1993: Surface temperature as an important parameter of plant stand. *Időjárás 97*, 259-267.

Antal, E., 1966a: Measurement of maximum water use in maize and alfalfa canopies (in Hungarian). *Beszámolók* 1964 II. Orsz. Meteor. Int., Budapest, 60-65.

Antal, E., 1966b: Potential evapotranspiration of some agricultural crops (in Hungarian). *Öntözéses Gazdálkodás, 4*, 69-86.

Antal, E., 1968a: New method for determining of potential evapotranspiration (in Hungarian). *Beszámolók 1967*. Orsz. Meteorológiai Int., Budapest, 452-460.

Antal, E., 1968b: *Forecast of Irrigation by Using Meteorological Elements*. Ph. D. Thesis, Budapest.

Antal, E., 1972: Is plant growth determined by internal water balance and turgor in the cells or by external factors? *Acta Agronomica, Hungarian Acad. Sci. 21*, 458-468.

Antal, E. and *Posza, I.*, 1967: Characteristics of evapotranspiration in maize stand. *Beszámolók* 1966. Orsz. Meteorológiai Int., 499-509.

Antal, E. and *Posza, I.*, 1970: Biological crop constants of differenr plants and their change during the growing season (in Hungarian). *Beszámolók* 1968. Orsz. Meteorológiai Int., 452-460.

Antal, E. and *Endrődi, G.*, 1972: Water demand and irrigation water demand of potato (in Hungarian). *Időjárás 76*, 223-233.

Antal, E., *Posza, I.* and *Tóth, E.*, 1975: Influence of weather and climate on use of artifical fertilizer (in Hungarian). *Időjárás 79*, 95-104.

Cselőtei, L., 1991: Basis of irrigation in growing of vegetables (in Hungarian). *GATE Hiv. Kiadv.*, Gödöllő, pp. 209.

Endrődi, G., 1979: Optimal evapotranspiration and rainfall for potato in Hungary (in Hungarian). *Beszámolók* 1977. Orsz. Meteorológiai Szolg., Budapest, 185-196.

Endrődi, G., 1973: Investigation on water use of sugar beet (in Hungarian). *Beszámolók* 1970. Orsz. Meteorológiai Szolg., Budapest, 147-154.

Endrődi, G., 1974: Agrometeorological basis of water demand and irrigation water need of sugar beet (in Hungarian). *Beszámolók* 1971. Orsz. Meteorológiai Sz., Budapest, 186-199.

Erdős, L., 1966: Measurement of potential evapotranspiration (in Hungarian). *Időjárás 70*, 129-135.

Fekete, L. and *Szilágyi, T.*, 1979: Water use and phenometrical parameters of sweet corn (in Hungarian). *Beszámolók* 1977. Orsz. Meteorológiai Szolg., Budapest, 196-206.

Huzulák, J. and *Matejka, F.*, 1992: Stomatal resistance, leaf water potential and hydraulic resistance of sugar beet plants. *Biol. Plantarum 34*, 291-296.

Kádár, F. and *Szilágyi, T.*, 1980: Optimal evapotranspiration of maize, climatic water deficit and its yield (in Hungarian). *Beszámolók* 1978. Orsz. Meteorológiai Szolg., Budapest, 156-167.

Kozma, F. and *Füri, J.*, 1974: Evapotranspiration of grape (in Hungarian). *Beszámolók* 1971. Orsz. Meteorológiai Szolg., 215-226.

Lawlor, D.W. and *Milford, G.F.J.*, 1975: The control of water and carbon dioxide flux in water stressed sugar beet. *J. Exp. Bot. 26*, 657-665.

Novák, J. and *Szilágyi, T.*, 1980: Data for evapotranspiration of cucumber (in Hungarian). *Beszámolók* 1978. Orsz. Meteorológiai Szolg., Budapest, 199-210.

Petrasovits, I., 1970: *Water Demand of Irrigated Plant Stands* (in Hungarian). Thesis, Hungarian Acad. Sci., Budapest.

Posza, I., 1978: Effect of soil water depth on evapotranspiration (in Hungarian). *Beszámolók* 1975. Orsz. Meteorológiai Szolg., Budapest, 210-218.

Posza, I., 1980: Evapotranspiration of canned vegetables (in Hungarian). *Beszámolók* 1978. Orsz. Meteorológiai Szolg., 226-232.

Ruzsányi, L., 1975: *Investigation of Evapotranspiration of Plant Canopies at Different Nutrition Level* (in Hungarian). Ph.D. Thesis, Budapest.

Ruzsányi, L., 1981: Influence of irrigation and fertilizers on yield and quality of sugar beet (in Hungarian). *Növénytermelés 30*, 363-370.

Ruzsányi, L., 1990: Water demand of sugar beet and effect of irrigation (in Hungarian). *Növénytermelés 39*, 423-429.

Stollár, A. and *Gergely, I.*, 1978: Evapotranspiration of young apple trees (in Hungarian). *Beszámolók* 1976. Orsz. Meteorológiai Szolg., Budapest, 206-215.

Szalóki, S., 1971: *Questions on Soil Water Level, Evapotranspiration and Irrigation* (in Hungarian). Ph.D. Thesis, Budapest.

Szlovák, S., 1979: *Investigation on Transpiration and Evapotranspiration of Maize* (in Hungarian). Ph.D. Thesis, Budapest.

Tóth, E., 1978: Evapotranspiration of maize at different levels of fertilizer and irrigation water (in Hungarian). *Beszámolók* 1975. Orsz. Meteorológiai Szolg., Budapest, 241-256.

Walkowszki, A., 1978: Effect of plant density on maize evapotranspiration (in Hungarian). *Beszámolók* 1975. Orsz. Meteorológiai Szolg., Budapest, 256-260.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 1, January–March 1995

Simple analytic model of horizontal wind turning

Ivica Vilibić

Hydrographic Institute of the Republic of Croatia,
Zrinsko-Frankopanska 161, 58000 Split, Croatia

(Manuscript received 3 October 1994; in final form 25 January 1995)

Abstract—By assuming the linearity of the wind field and using data from two meteorological measuring stations, based on analytic relations, the model calculates the quantities which describe the horizontal wind turning and serve as input data for the transport and diffusion models. The model has been applied within the Gaussian model and the results obtained are satisfactory.

Key-words: wind field, transformation of coordinates, condensation factor, plume axis, application within a larger model.

1. Introduction

Modeling of transport and diffusion processes in the atmosphere, sea and land play a very significant role nowadays. Industrialization and pollution of the Earth have produced the necessity of understanding and description of processes which take place on and inside it. To describe the atmospheric transport and diffusion processes on a mesoscale, Gaussian, K-, and Monte Carlo models are being applied successfully. Because of its analyticity, the Gaussian model is one of the most widely used models, but its limitation is that, because of irreal representation of the wind field, it is not able to describe the wind turning in the horizontal plane.

In this work a small contribution is given to the description of the horizontal turning of the smoke plume by using a set of simple analytic equations. It may be applied in orographically weakly developed regions where mesoscale horizontal wind turning occurs. Horizontal wind turning may be caused by the different roughnesses of the ground or urbanization in a region as well as by discontinuities between the water and dry land surfaces. Some descriptions about these problematics are shown in the article by *Šinik* (1982).

This model takes the coordinates (x,y) of the place where concentration of the atmospheric constituents is wanted to be known and calculates the transformed coordinates (x',y') and the condensation factor e, which describe the effects of wind turning and serve as input parameters for the transport and diffusion models. The wind field is modeled by the input data from two measuring meteorological stations (the simplest case), making use of the exponential law of the vertical variation of the wind speed and the linearization of the wind speed gradient. The assumptions of this model are chosen such that the transformation of coordinates may be described by analytic relations.

2. Input data. Wind field

Input data of this model are the coordinates of two measuring meteorological stations as well as the speed and direction of wind at 10 meters above the ground, which are being measured by these stations. The domain can range between 10 and 100 square kilometers. We denote the coordinates of the two stations by (x_1,y_1) and (x_2,y_2) and assume that they are placed down the wind.

In such models it is often necessary to determine the wind at a certain height above the ground. To determine the wind speed at any height, exponential law of the vertical change of the wind speed (*Well* and *Brower*, 1984) can be used:

$$u_{1H} = u_1 \left[\frac{z}{10} \right]^p , \tag{1}$$

$$u_{2H} = u_2 \left[\frac{z}{10} \right]^p , \tag{2}$$

where u_{1H} and u_{2H} are the wind speeds at a height z above the stations labelled 1 and 2, respectively, and p is an exponent given by the relationships of the similarity theory (*Panofsky* and *Dutton*, 1984).

A schematic review of the turning of plume is given in *Fig. 1.* The distance from the source I_s (which represents the plume source) to some point (x_0,y_0) nearest to input point (x,y) represents transformed coordinate x', while transformed coordinate y' is defined as the shortest distance from point (x,y) to axis x'. The most general description of the turning of plume axis x' in this model with two measuring stations assumes that the domain is divided into three regions.

Region I occupies the space from the source of emission to the station 1. Wind field is uniform and parallel to the x axis, that is:

$$u = u_{1H}, \tag{3}$$

$$v = 0. \tag{4}$$

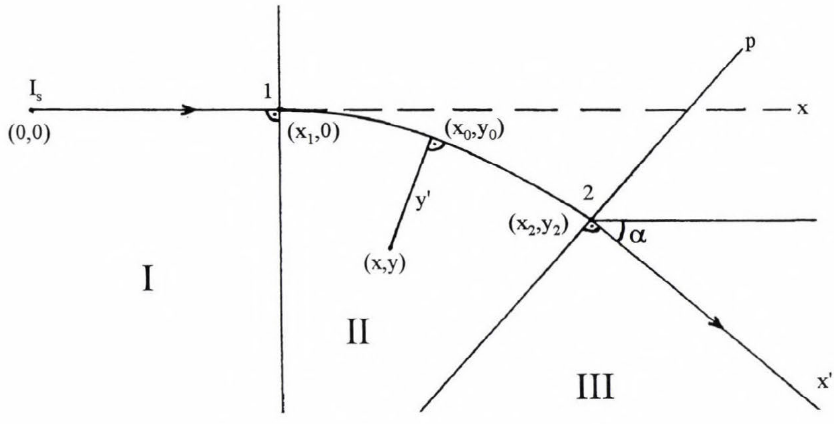


Fig. 1. Scheme of horizontal wind turning.

Region II represents the space of the plume turning, which is defined as a space between stations 1 and 2. It is assumed that the air flow turns it equally in the given region, so that the wind speed gradient in y-direction disappears, and that the same gradient in the x-direction is constant. Then, by expanding the wind field into a Taylor series, we can write it in this form:

$$u = u_{1H} + \frac{\partial u}{\partial x}(x - x_1) + \dots , \tag{5}$$

$$v = \frac{\partial v}{\partial x}(x - x_1) + \dots , \tag{6}$$

where the wind gradients are given by

$$\frac{\partial u}{\partial x} = \frac{u_{2H}\cos\alpha - u_{1H}}{x_2 - x_1}, \tag{7}$$

$$\frac{\partial v}{\partial x} = \frac{u_{2H}\sin\alpha}{x_2 - x_1}. \tag{8}$$

Region III represents the space away from station 2 where the direction of wind is parallel to the wind direction at this station, i.e.

$$u = u_{2H}\cos\alpha , \tag{9}$$

$$v = u_{2H}\sin\alpha . \tag{10}$$

3. Mathematical formulation

3.1 Region I

In this region no wind turning occurs, so the transformation of coordinates and the condensation parameter can be described by the simple equations:

$$x' = x, \tag{11}$$

$$y' = y, \tag{12}$$

$$e = 1. \tag{13}$$

3.2 Region II

In this region the plume turning occurs. By expanding into the Taylor series, and using Eqs. (5) and (6), components of the wind speed are

$$u = \frac{dx}{dt} = u_{1H} + \frac{\partial u}{\partial x}(x - x_1), \tag{14}$$

$$v = \frac{dy}{dt} = \frac{\partial v}{\partial x}(x - x_1), \tag{15}$$

where $\partial u/\partial x$ and $\partial v/\partial x$ are given by Eqs. (7) and (8). Equating dt from Eqs. (14) and (15) and integrating, we obtain the trajectory of a particle in the plume axis or representation of the x'-axis in the (x,y) coordinate system

$$y = b\left[x - x_1 - a\ln\left(1 + \frac{x - x_1}{a}\right)\right], \tag{16}$$

where

$$a = \frac{u_{1H}}{\partial u/\partial x}; \qquad b = \frac{\partial v/\partial x}{\partial u/\partial x}. \tag{17}$$

Relationship Eq. (15) and all further relations where a and b appear are valid if $\partial u/\partial x \neq 0$.

Determination of the coordinates (x_0,y_0) which represent the nearest point to the input point (x,y) on the plume axis x' is based on calculating the coordinates of the intersection of curve (16) and the straight line determined by points (x_0,y_0) and (x,y). Knowing the slope of the tangent at the plume axis at point (x_0,y_0)

$$k_t = \frac{b\,(x_0 - x_1)}{a + x_0 - x_1}, \tag{18}$$

we can establish the equation of the normal at the plume axis at (x_0,y_0)

$$y - y_0(x_0) = -\frac{a + x_0 - x_1}{b\,(x_0 - x_1)}\,(x - x_0), \tag{19}$$

from which x_0 may be calculated by iteration

$$x_0 = -\frac{y - y_0(x_0)}{x - x_0}\,(x_0 - x_1)\,b - a + x_1. \tag{20}$$

The arch length of the plume axis x' from the point x_1 to a x_0 is given generally by

$$s(x_1,x_0) = \int_{x_0}^{x_1} \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx. \tag{21}$$

Applying Eq. (21) at Eq. (16) we would get a much more complicated relation, so in this work $s(x_1,x_0)$ is modeled by the 'trial-and-error' method (we assumed the form of equation and determine the parameters by 'adjusting') in the following way

$$s(x_1,x_0) = \frac{1}{\cos\dfrac{\alpha_0}{3.3}}\sqrt{(x_1 - x_0)^2 + y_0^2}, \tag{22}$$

where

$$\alpha_0 = arctg\frac{bx_0}{a + x_0}. \tag{23}$$

Using the quantities calculated above, the relations for transformation of coordinates (x,y) into (x',y') are given by

$$x' = x_1 + s(x_1, x_0)\,, \tag{24}$$

$$y' = \sqrt{(x - x_0)^2 + (y - y_0)^2}\,. \tag{25}$$

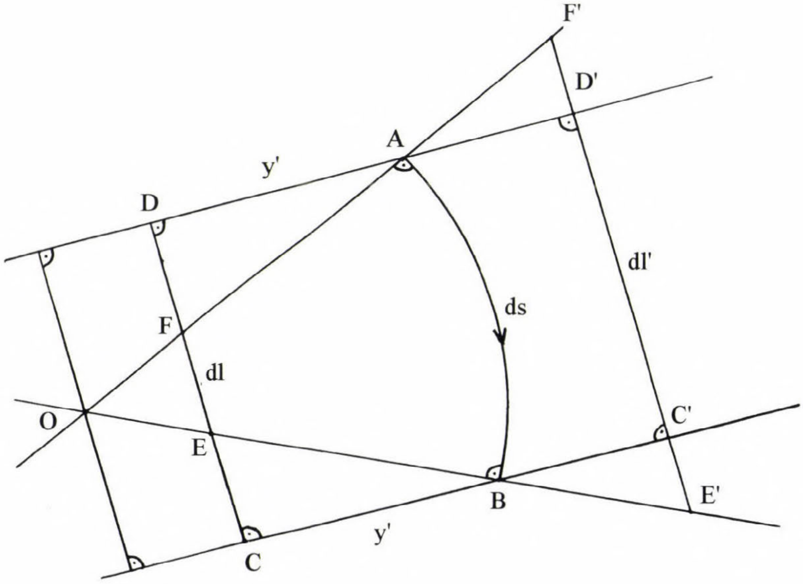


Fig. 2. Scheme of determining condensation factor.

The plume condensation factor *e* is obtained by assuming that the condensation (or the dilution) equals the ratio of the areas of non-curved and curved plume (*Fig. 2*). Defining the plume axis by the arch AB, factor e is defined by the ratio of areas of the 'rectangle' ABCD (dP_1) and figure ABEF (dP_2) for the case of internal motion (concave part of domain), while for the case of external motion (convex part of domain) factor *e* is defined by the ratio of areas of the figures ABC′D′ (dP_1) and ABE′F′ (dP_2)

$$e = \frac{dP_1}{dP_2}\,. \tag{26}$$

The area ABCD is given by

$$dP_1 \approx y'\, ds, \tag{27}$$

and ABEF by

$$dP_2 = \frac{1}{2} R\, ds - \frac{1}{2}(R - y')\, dl, \tag{28}$$

where R represents the radius of plume axis curvature OA (or OB), which is mathematically defined by

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}} \tag{29}$$

or substituting Eq. (16) into Eq. (29)

$$R = \left|\frac{a}{b}\right| \left(1 + \frac{x_0 - x_1}{a}\right)^2 \left[1 + \frac{b^2 (x_0 - x_1)^2}{(a + x_0 - x_1)^2}\right]^{3/2}. \tag{30}$$

The radius of curvature R has been taken into account when modeling e because of its excellent properties for description of turning of the plume axis.

Because dl is infinitesimal, it may be calculated from the ratio of the similar triangle OAB and rectangle ABCD

$$dl = \frac{R - y'}{R}\, ds. \tag{31}$$

In the case when the input point (x,y) is on the part of the region outside of the arc, i.e. if we consider the dilution, then the area ABE′F′ is

$$dP_2 = \frac{1}{2}(R + y')\, dl' - \frac{1}{2} R\, ds, \tag{32}$$

where dl' is calculated from the triangles OE′F′ and OAB

$$dl' = \frac{R + y'}{R}\, ds\,, \tag{33}$$

while Eq. (26) is valid for dP_1. Putting relations (31) and (33) into (28) and (32), respectively, we become able to unify the calculation of dP_2 in both cases

$$dP_2 = \left[1 + \frac{1}{2}\frac{y'}{R}\, sgn\,(x - x_0)\right] y'\, ds\,, \tag{34}$$

where x is input coordinate of the point, x_0 is the point given by relation (20), and *sgn* is sign function. It is obvious that for the internal part of the plume there is $x < x_0$ ($e < 1$) and for the external part there is $x > x_0$ (e > 1) (see Fig. 1).

Substituting Eqs. (34) and (27) into (26), the condensation factor e is defined by

$$e = \frac{2R}{2R + y'\, sgn(x - x_0)}\,. \tag{35}$$

This relation does not hold in case $y' sgn\,(x - x_0) < -R$ because in that case the triangle OAB is completely contained in ABCD, so e must be calculated by a linear extrapolation of the Eq. (35), accordingly

$$e = 1 - \frac{y'\, sgn(x - x_0)}{R}\,. \tag{36}$$

The complete set of equations for calculating e in part II is

$$e = \frac{2R}{2R + y'\, sgn(x - x_0)}\,; \quad \text{if} \quad y' sgn(x - x_0) \geq -R$$

$$= 1 - \frac{y' sgn\,(x - x_0)}{R}\,; \quad \text{if} \quad y' sgn\,(x - x_0) < -R\,. \tag{37}$$

3.3 Region III

In this region, which is separated from the previous one by the straight line p (see Fig. 1)

$$p \equiv y - y_2 = -\frac{1}{tg\,\alpha}(x - x_2), \tag{38}$$

the plume is moving along a straight line so that

$$e = 1 \tag{39}$$

or, there is no plume condensation or dilutation.

Transformation of coordinates x,y into x',y' is made by using the following relations

$$x' = x_1 + s(x_1, x_2) + \sqrt{(x_v - x_2)^2 + (y_v - y_2)^2}, \tag{40}$$

$$y' = \sqrt{(x - x_v)^2 + (y - y_v)^2}, \tag{41}$$

where (x_v, y_v) is the point on the plume axis nearest to the input point, and it is defined by

$$x_v = \frac{(y - y_2)\,tg\,\alpha + x_2(1 - tg^2\alpha)}{1 + tg^2\alpha}, \tag{42}$$

$$y_v = y - \frac{1}{tg\alpha}(x_v - x). \tag{43}$$

3.4 *The case* $\alpha = 0$

All the equations given above (for the regions II and III) are defined for case $\alpha \neq 0$, while in case $\alpha = 0$, where there is no wind turning at all inside the whole domain, relations (11), (12) and (13) for the region I are used in whole domain.

3.5 *The case* $\partial u/\partial x = 0$

If the gradient of wind along x happens to disappear, which means $u_{2H}\cos\alpha = u_{1H}$, then the parameters a and b become infinite. That is why we have to reformulate the relations where $\partial u/\partial x$, a and b appear.

The Taylor expansion of relation (4) is in this case

$$u = u_{1H} = \frac{dx}{dt}, \tag{44}$$

$$v = \frac{\partial v}{\partial x}(x - x_1) = \frac{dy}{dt}, \tag{45}$$

from which we derive equation of the plume axis in region II

$$y = \frac{1}{u_{1H}} \frac{\partial v}{\partial x} \frac{(x - x_1)^2}{2}. \tag{44}$$

Relationship (22) turns into

$$s(x_1,x_0) = \frac{1}{2}\left[(x - x_1)\sqrt{1 + \left[\frac{1}{u_1}\frac{\partial v}{\partial x}(x - x_1)\right]^2} + \frac{u_1}{\partial v/\partial x} Arsh\left[\frac{1}{u_1}\frac{\partial v}{\partial x}(x - x_1)\right]\right], \tag{45}$$

while formula (30) is transformed into

$$R = \frac{u_1}{\partial v/\partial x}\left[1 + \left[\frac{1}{u_1}\frac{\partial v}{\partial x}(x - x_1)\right]^2\right]^{3/2}.$$

In this way all the possibilities of occurrence of the wind field are defined, so turning of the plume axis is defined for all the combinations of input parameters where $|\alpha| < 90°$ holds. By calculating the transformed coordinates x',y' and the condensation factor e, we obtain the complete definition of parameters needed when applying various transport and diffusion models (one of which is the Gaussian model).

4. Application and results

This model has been applied within the Gaussian transport and diffusion model for continuous sources, where it has served to describe spreading of pollutants in the planetary boundary layer. The distribution of concentrations obtained by the Gaussian model has given a fairly good description of the spreading of pollutants in the atmosphere, taking into account the horizontal turning of the plume. Some results (for unstable, neutral and stable atmosphere, respectively) are shown in *Fig. 3* for constituent SO_2. Horizontal distance between two nearest points (circles) are 500 meters and the area of the circle is proportional to the concentration of pollutants. Wind direction in the first 3000 meters is parallel two the x axis, from 3000 meters it continuously turns towards angle of 45 degrees at distance 8000 m, and further it does not vary. It is observed that the condensation factor e has a small effect in the region near the plume axis (where the largest concentrations occur) and it is approximately equal to 1, while at largest distances from the plume axis the effect of it becomes bigger. Because of the smaller concentrations than inside the plume axis, its total effects are quite small.

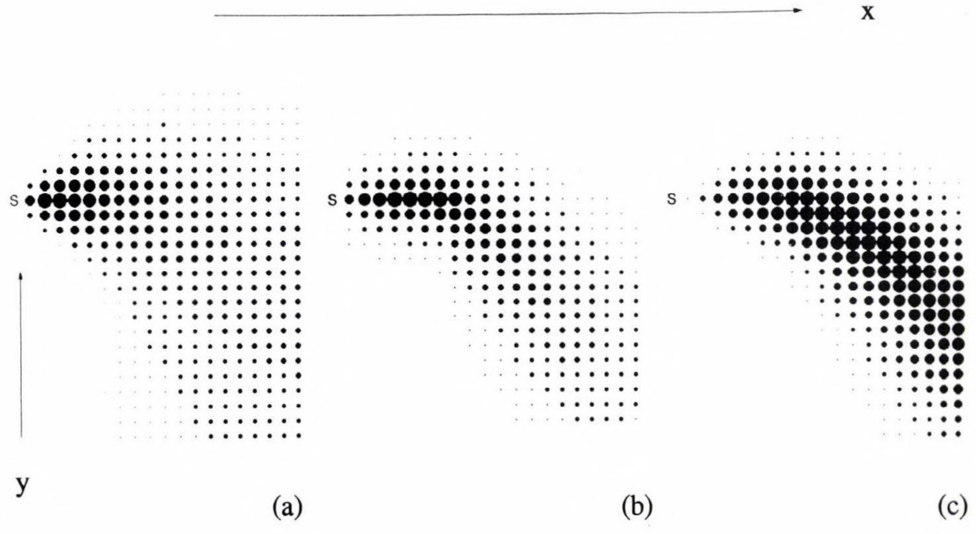


Fig. 3. Spreading of pollutants in (*a*) unstable, (*b*) neutral, and (*c*) stable atmosphere.
S: source of pollutant emission.

5. Conclusion

The simple analytic model of horizontal wind turning is applicable within the larger models which describe the transport and diffusion processes of atmospheric constituents. Based on the input data of the speed and direction of wind and the positions of two measuring meteorological stations the wind field is described by analytic equations within the whole considered region. By mathematical procedures we obtain the trajectory of constituents of the atmosphere in the plume centre (axis), the transformed coordinates which represent the distance from the observed point to the plume axis, and also the distance of the constituents transport on the plume axis.

The condensation factor is also defined which describes condensation (or dilution) of the plume depending on the x' axis turning and input coordinates of the points. These quantities represent input parameters for the transport and diffusion models, for example the Gaussian plume model, which uses the trajectories obtained by this model for calculating the transport of atmospheric constituents.

Further extensions of this model are possible if we include more than two measuring stations and also by taking into account the vertical component of the wind field induced by the orography. To describe the wind field the objective analysis method may be used, as well. Such representation would not be analytic, because we would have to apply numerical methods.

Acknowledgements—I wish to thank *Mr. Nadežda Šinik* for his unselfish advices while the model was being built up. Also I thank *Artic Sergio* for giving computer support and *Ljerka Zekanovic* for lectoring the article.

References

Panofsky, H.A. and *Dutton, J.A.*, 1984: *Atmospheric Turbulence*. John Wiley & Sons, New York, 397 pp.

Šinik, N., 1982: Mesoscale variation of average airflow in application to time integrated concentration Gaussian models. *Atmos. Environ. 16*, 2061-2069.

Well, J.C. and *Brower, R.P.*, 1984: Un updated Gaussian plume model for tall stacks. *JAPCA 34*, 818-827.

BOOK REVIEW

Ian N. James: **Introduction to Circulating Atmospheres**. Cambridge Atmospheric and Space Science Series, Cambridge University Press, 1994, Cambridge, 422 numbered pages, numerous figures.

This book is one of the Cambridge Atmospheric and Space Science Series. It was born from the expansion of university courses that the author gave on the topic of atmospheric circulation. In the preface the author addresses his book to students familiar with the basic concepts of atmospheric dynamics at an introductory university level and researchers who are research interested in the atmospheric circulation. However, this book is undoubtedly more than a simple coursebook. It is a well-rounded, thorough text that strikes a nice balance between mathematical theory and meteorological interpretation. The book consists of ten chapters. 1. The governing physical laws. 2. Observing and modelling of global circulation. 3. The atmospheric heat engine. 4. The zonal mean meridional circulation. 5. Transient disturbances in the midlatitudes. 6. Wave propagation and steady eddies. 7. Three-dimensional aspects of the global circulation. 8. Low frequency variability of the circulation. 9. The stratosphere. 10. Planetary atmospheres and other fluid systems.

Chapters 1 to 7 summarize the classical theory of the atmospheric circulation and present a large amount of figures and maps based on atmospheric observations. A large part of the observed data used in this book has been analyzed at the European Centre for Medium Range Weather Forecasts. Quite a large amount of new data have been analyzed and the author's scientific activity up till now guaranties the outstanding quality of analysis techniques. This feature makes this book the most valuable and up-to-date collection of figures on the topic of atmospheric circulation. In these chapters Dr. James has not made an attempt to write a review of the state-of-art literature on the atmospheric circulation. Indeed, he makes an effort to present the simplest conceptual (and mathematical) models of the phenomena which are in good accordance with the observations, thus avoiding the use of much more sophisticated mathematics of recent studies, unless they provide a substantially better theoretical approach. A good example of this attempt is the description of the theory of baroclinic instabilities by the simple but really adequate Eady model.

An additional outstanding feature of this book is the strict distinction between the notion of Lagrangian and Eulerian atmospheric circulations. Most of the previous textbooks have not dealt in details with the Lagrangian circulation. Moreover, they have not emphasized the differences between the two approaches, although the realization of these differences had led to the exact understanding of the Eulerian circulation in the upper troposphere and the stratosphere. This fact makes this text an excellent first book on atmospheric dynamics for researchers in the field of large scale atmospheric transport processes. This statement is especially valid taking into consideration that Chapter 9 gives a detailed description of the circulation of the stratosphere, which plays much more important role in the transport processes than it was thought earlier.

While the above-mentioned Chapter 9 gives an overview of the present knowledge of stratospheric circulation, in Chapter 8 the variability of circulation is presented on the base of the theory of dynamical systems. This chapter makes the book an up-to-date textbook on the atmospheric circulation of the Earth, while Chapter 10 makes it a complete textbook on circulating atmospheres. This last chapter discusses the planetary atmospheres on the simple but fruitful realization that terrestrial circulation is only one of the possible circulations. What specifies circulating atmospheres, is the geometrical properties of the motions of planets: radius of the planet, speed of rotation (Coriolis parameter), distance from the Sun (solar constant). The text in the first seven sections is organized in a way, that changing the above parameters readers can get a detailed description of the dynamics of any planetary atmospheres. It is really interesting to see that the Eady model of baroclinic instabilities works for other planets, not only for the Earth. One subsection deals with Saturn's moon Titan, which has a stick atmosphere in which prebiotic complex organic solids form and fall down onto the surface.

This book constitutes an up-to-date overview of circulating atmospheres. Because of its relative simplicity and plenty of carefully analyzed data it will serve as a valuable reference volume to researchers in the filed of dynamic meteorology and climatology.

I. Szunyogh

NEWS

In memoriam J. Kakas
(1909–1994)

Dr. József Kakas, the well-known Hungarian classical climatologist, died on 4 October 1994. He was, among other charges, the Editor of the journal *Időjárás* between the years 1953 and 1968. He did this job with a high-level scientific and technical competence. Even as a retired scientist he participated in the editional work until 1990.

J. Kakas was born on 31 July 1909 in Zalaegerszeg. He attended a monastic secondary school (S.P.) in Nagykanizsa where he sat for the final examination in 1928. He took the master's degree in geography and history at the Pázmány Péter University of Budapest. He entered service of the Hungarian Meteorological Institute in 1937. His first research area was the investigation of precipitation and humidity distributions in Hungary as well as the study of wind climatology of the country. In some years he became an excellent climatologist approaching the atmospheric processes from the viewpoint of geography. The results of his research were published in several papers and books in the fifties. On the basis of natural criteria, he established new climatic regions in Hungary. Appreciating his scientific activity the Hungarian Academy of Sciences awarded him the degree of Ph. D. in 1962.

Dr. Kakas was appointed the head of the Department of Climatology of the Institute in 1953 and he became the chief of the Division of Climatology and Hydrology in 1963. In this period he directed the so-called Balaton Project aiming to reveal the climatology of the lake. This Project resulted in more than hundred publications prepared by the scientists involved. J. Kakas retired after a long and successful carrier in 1971. However, even after his retirement, he edited a book entitled *The Climate of Balaton* which was published in 1974 by the Hungarian Meteorological Service. In this volume the authors analyse and discuss the climatic, radiative, energetic and hydrological systems and other peculiarities of Lake Balaton. In addition to the work of *L. Lóczy* and *J. Cholnoky* at the beginning of the 20th century this is the most detailed scientific monograph about the lake.

An outstanding editorial achievement of J. Kakas was the Climate Atlas of Hungary published in 1960 and also a second volume of this publication containing detailed climatic data of the country. The success of his efforts is well demonstrated by the fact that, for the Climate Atlas of Europe published by the World Meteorological Organisation, the maps of the distribution of several climatic elements were prepared by a Hungarian working group headed by him. After a careful working of several years the Atlas was issued in 1970 and had a great success.

The determining feature of the life of Dr. Kakas was the accurate, conscientious and correct work. Several meteorologists of the rising generation, inherited these qualities from him.

The memory of József Kakas will forever remain in the hearts of his friends working in the fields of meteorology, geography and hydrology.

M. Kéri

Scientific Days '94 on Meteorology

The traditional annual Scientific Days on Meteorology were organized by the Scientific Committee on Meteorology of the Earth Sciences Class of the Hungarian Academy of Sciences and the Hungarian Meteorological Service (HMS) in the Center of the Federal Chamber of Technical and Scientific Societies in Budapest on 17th and 18th November 1994. The subject of the program was weather forecasting. In the frame of three sessions altogether 21 papers were presented. Because of the large number of presentations 5 contributions were exhibited as poster.

The program was introduced by two foreign authors' papers (*J.-F. Geleyn*, Météo-France and *J. McGinley*, NOAA, FSL), moreover, in the compilation of additional 5 papers also foreign, American, French and Swiss scientists as co-authors took part. Among the Hungarian lecturers, even scientists from the Water Resources Research Center (VITUKI) and the Meteorological Department of Eötvös Loránd University (MD-ELTE) should be mentioned. Further, the presentations are shortly shown but the name of only the speaker of the authors is given.

J.-F. Geleyn talked about ALADIN project brought into existence by French proposal. The ALADIN is a fine mesh variant of the ARPEGE model for Central and Eastern Europe. Presently, the model is run in Toulouse and the output is transmitted to the users by satellite. *J. McGinley* gave information about activity of local weather offices in U.S.A., amounting to 150. During the last ten years the available weather information was about tripled. The LAPS (Local Analysis and Prediction System) developed in FSL enables to display gridded weather data (from surface, satellite, radar and aircraft) to the forecasters. *G. Götz* studied the problem of predictability on the basis of the chaos theory. He pointed out the high sensitivity to the initial conditions which defines a theoretical limit to the predictability. Furthermore, he informed about methodological bases of the ensemble forecasts overtaking this difficulty. *I. Szunyogh* delivered two papers about the results of common researches carried out together co-workers of NMC. In the first one local stability parameters were presented through some examples. The Arnold method was concerned which is capable of examining only stationary solutions of adiabatic models. The other paper dealt with problems of optimal perturbations. A numerical experiment series was shown in which the optical perturbations were performed by two varieties of medium range model used in NMC.

A global spectral shallow water model developed in NCAR was adapted at MD-ELTE into which the topographical effect was incorporated. In the attempts carried out with the model the sensitivity of the model and unstable perturbations to the topography was investigated (*B. Kádár*). The formation and dynamics of frontal waves, so important in view of weather forecasting, were studied in the paper by *A. Horányi*. He wanted to discover which factors in the initial conditions are favorable to the formation and development of waves. The attempts were implemented by adjoint application of ARPEGE/ALADIN model.

As known, in numerical weather prediction models based on primitive equations the filtration of gravitational waves is necessary. *G. Radnóti* presented an initialization method and searched for the effectivity of the recursive and non-recursive filters and the interaction of the dissipative forcings and filtering. In another paper it was studied how the covariance of forecast errors could be derived *(D. Dévényi)*. He examined, by using one- and two-level models and statistical characteristics of them, how the errors, both being in the initial conditions and resulting from the approaching feature of the model, developed during the forecasting period. In addition to weather forecasting the climate prognosis was also included in the program of the session. In order to obtain expectable regional climate changes a medium resolution meso-scale model was embedded into T42 variant of GCM (*J. Bartholy*), and the orography and roughness of the surface were also incorporated. In this way she succeeded in reconstructing the historical data series and estimating the temperature and precipitation scenarios related to CO_2 doubling.

Á. Horváth talked about recently installed workstation of the forecasting service, pointing out main functions of it: spatial and temporal data assimilation (e.g. use of uniform map projection), preparation of spatial and temporal cross-sections, complete data handling. The newest variant (ITTP 4.02 model) of the program extracting atmospheric profiles from TOVS data by NOAA is available in HMS. *É. Borbás'* paper presented an intercomparison study of the data which were produced by satellite and radiosondes, and prediction model.

The last, third session was devoted to the subject of operational forecasting. *Á. Takács* informed about the forecasting activity carried out as a duty obliged to the state. This presentation was closely connected with the next paper given by *M. Sallai* about the work of the aviation meteorological center of the HMS. In addition to servicing the international airlines the performance of requirements of private flights plays an increasing role. In summer time a storm warning service is operating at Lake Balaton. A decisive technique was developed for forecasting the storms associated with convective systems (*Á. Zsikla*).

G. Csima rendered account of Hungarian experiences in connection with application of one-month forecasting method developed by the UK Meteorological Office. After then two papers were presented by co-workers of VITUKI. Both authors (*P. Bartha* and *G. Bálint*) emphasized the importance of meteorological forecasts in the hydrological activity. Because of stratospheric ozone depletion the claim to forecast UV-B radiation is increasing. A work showed that the intensity of UV-B radiation depends in high degree on the weather conditions as well, and forecasting may be made only taking into consideration both the ozone content and the weather situation (*P. Németh*).

At the end of the session two reports were given about the utilization of weather forecasts (*M. Bóna* and *A. Maller*). They informed about both the result of a public opinion test related to the forecasts and the distribution of the claims with respect to the users. The special forecast products could be ranged into four groups: medical meteorology, protection of environment, warning and informing the media.

The posters were concerned with very various topics; just in some words: Regionalization of global climate prediction (*J. Bartholy et al.*), Cloud classification by cluster analysis (*M. Diószeghy*), Forecasting for sport flights by using GRID and TEMP data (*A. Fövényi*), Estimation of rainfall efficiency by combined analysis of radar and satellite information (*J. Kerényi*), A warning system for water quality of Danube (*G. Pintér*, VITUKI).

T. Tänczer

ATMOSPHERIC ENVIRONMENT

an international journal

To promote the distribution of Atmospheric Environment *Időjárás* publishes regularly the *contents* of this important journal. For further information the interested reader is asked to contact *Dr. P. Brimblecombe,* School for Environmental Sciences, University of East Anglia, Norwich NR 7TJ, U.K.

Volume 28 Number 20 1994

Volume 28 Number 21 1994

Volume 28 Number 22 1994

The Indoor Air '93 Congress

Regular Papers

Volume 29 Number 1 1995

Volume 29 Number 2 1995

Volume 29 Number 3 1995

NOTES TO CONTRIBUTORS

The purpose of *Időjárás* is to publish papers in the field of theoretical and applied meteorology. These may be reports on new results of scientific investigations, critical review articles summarizing current problems in certain subject, or shorter contributions dealing with a specific question. Authors may be of any nationality but papers are published only in English.

Papers will be subjected to constructive criticism by unidentified referees.

* * *

The manuscript should meet the following formal requirements:

Title should contain the title of the paper, the names(s) of the author(s) with indication of the name and address of employment.

The title should be followed by an *abstract* containing the aim, method and conclusions of the scientific investigation. After the abstract, the *key-words* of the content of the paper must be given.

Three copies of the manuscript, typed with double space, should be sent to the Editor-in-Chief: *P.O. Box 39, H-1675 Budapest,* Hungary.

References: The text citation should contain the name(s) of the author(s) in Italic letter or underlined and the year of publication. In case of one author: *Miller* (1989), or if the name of the author cannot be fitted into the text: (*Miller,* 1989); in the case of two authors: *Gamov* and *Cleveland* (1973); if there are more than two authors: *Smith et al.* (1990). When referring to several papers published in the same year by the same author, the year of publication should be followed by letters a,b etc. At the end of the paper the list of references should be arranged alphabetically. For an article: the name(s) of author(s) in Italics or underlined, year, title of article, name of journal, volume number (the latter two in Italics or underlined) and pages. E.g. *Nathan, K. K.,* 1986: A note on the relationship between photosynthetically active radiation and cloud amount. *Időjárás 90,* 10-13. For a book: the name(s) of author(s), year, title of the book (all in Italics or underlined with except of the year), publisher and place of publication. E.g. *Junge, C. E.,* 1963: *Air Chemistry and Radioactivity.* Academic Press, New York and London.

Figures should be prepared entirely in black India ink upon transparent paper or copied by a good quality copier. A series of figures should be attached to each copy of the manuscript. The legends of figures should be given on a separate sheet. Photographs of good quality may be provided in black and white.

Tables should be marked by Arabic numbers and provided on separate sheets together with relevant captions. In one table the column number is maximum 13 if possible. One column should not contain more than five characters.

Mathematical formulas and *symbols:* non-Latin letters and hand-written marks should be explained by making marginal notes in pencil.

The final text should be submitted both in manuscript form and on *diskette.* Use standard 3.5" or 5.25" DOS formatted diskettes for this purpose. The following word processors are supported: WordPerfect 5.1, WordPerfect for Windows 5.1, Microsoft Word 5.5, Microsoft Word 6.0. In all other cases the preferred text format is ASCII.

* * *

Authors receive 30 *reprints* free of charge. Additional reprints may be ordered at the authors' expense when sending back the proofs to the Editorial Office.

Published by the Hungarian Meteorological Service

Budapest, Hungary

INDEX: 26 361

HU ISSN 0324-6329

IDŐJÁRÁS

QUARTERLY JOURNAL
OF THE HUNGARIAN METEOROLOGICAL SERVICE

CONTENTS

VOL. 99 * NO. 2 * APRIL–JUNE 1995

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

Editorial Office: P.O. Box 39, H-1675 Budapest, Hungary or
Gilice tér 39, H-1181 Budapest, Hungary
E-mail: gmajor@met.hu; Fax: (36-1) 290-7387

Subscription from customers in Hungary should be sent to the Financial Department of the Hungarian Meteorological Service, Kitaibel Pál u. 1, H-1024 Budapest. The subscription rate is HUF 2500.

Abroad the journal can be purchased from the distributor: KULTURA, P.O. Box 149, H-1389 Budapest. The annual subscription rate is USD 55.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

Editorial

In January 1995, after 15 years of editorial work, *Prof. Ernő Mészáros*, retired from the position of Editor-in-Chief of *Időjárás*. During those 15 years the scientific journal of the Hungarian Meteorological Service increased its scientific standard, had an attractive presentation and was regularly published in each quarter of the year. *Prof. Mészáros* continues his scientific activity at the University of Veszprém (Hungary). We wish him good health and further successes!

The President of the Hungarian Meteorological Service, *Dr. Iván Mersich*, nominated me as Editor-in-Chief for the next years. No changes in the policy of the journal are planned. Most of the members of the previous editorial board will kindly continue to help the editorial work in realizing the basic purpose of the Journal: to publish high quality articles from any field of the atmospheric sciences written in English language.

As regards my scientific background. I graduated from mathematics, physics and meteorology at the Eötvös Loránd University in Budapest. After a year of work in thefield of agrometeorology I became engaged in studies of atmospheric radiation. A UN fellowship gave me the opportunity to spend a year to study the utilization of radiation data measured by meteorological satellites with such famous supervisors as *K. Ya. Kondratyev, V. E. Suomi, T. H. VonderHaar* and *J. S. Winston*. Taking part in the activities of the international radiation community I was elected member of the International Radiation Commission of the IAMAP between 1979–1987 and of the Working Group on Radiation and Turbidity Measurements of CIMO/WMO between 1984–1992. I spent more than 30 years with the Hungarian Meteorological Service. Currently I am leading a research group that deals with satellite, climate impact and agrometeorological problems. In editing of *Időjárás* I receive a valuable help from *Ms. M. Antal*.

Next year the *Időjárás* will celebrate its 100th birthday. It is one of the oldest meteorological journals in the world. I express my sincere thanks to the authors and the readers for their interest in our Journal.

Dr. G. Major
Research Professor

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 2, April–June 1995

Circumsolar radiation calculated for various aerosol models

Mária Putsay

Hungarian Meteorological Service,
P.O. Box 39, H-1675 Budapest, Hungary

(Manuscript received 16 February 1995; in final form 3 May 1995)

Abstract—Theoretical calculations of circumsolar radiance and irradiance are carried out for various aerosol models: two maritime, two urban, two background and one mountain aerosol models. It is found that, in general, the angular distribution of the circumsolar radiance function is determined by the aerosol size distribution, whereas the amount of the radiance depends mainly on the air mass (which depends on the sun's elevation) and the aerosol optical depth. The ratios of circumsolar to direct solar irradiance were calculated as a function of the aerosol optical depth. The ratio at 5° is less than 5% in most of the cases.

Key-words: circumsolar radiation, direct radiation, diffuse radiation, global radiation.

1. Introduction

The circumsolar radiation is the scattered sky radiation in the forward directions near to the direction of the sun. Because the aerosol particles scatter mainly forward, the radiance in the circumsolar region is much higher than in other directions.

The investigation of the circumsolar radiation is important for several reasons:

(1) The direct solar irradiance measured by pyrheliometers have a systematic error due to the fact that the pyrheliometer measures not only the direct solar radiation but some part of the circumsolar radiation, too. This fact complicates the comparability of pyrheliometric measurements in case of different instrument geometry.

(2) If the global solar irradiance is determined by measuring direct and diffuse radiation independently (*WCRP-64*, 1991) an error can arise if the pyrheliometer measured and the diffusometer excluded circumsolar radiations are different (*Major*, 1992). Accurate measurements of global solar radiation are necessary for monitoring of possible climate changes.

(3) Accurate knowledge of the incoming direct solar energy flux and of the energy flux of the circumsolar radiation is needed at the planning of solar power plants.

Calculations of the circumsolar radiation have been carried out by several authors (*Grassl*, 1971; *Eiden*, 1968; *Green at al.*, 1971; *Fröhlich* and *Quenzel*, 1974; *Putsay*, 1980; *Major*, 1980; *Thomalla et al.*, 1983). Some of these calculations (*Grassl*, 1971; *Eiden*, 1968; *Green et al.*, 1971; *Fröhlich* and *Quenzel*, 1974; *Putsay*, 1980) were made for a few wavelengths only without integration over the whole solar spectral region. *Eiden* (1968) and *Green et al.* (1971) solved the inverse scattering problem by estimating the concentration and size distribution of aerosol particles from circumsolar radiation measurements. *Fröhlich* and *Quenzel* (1974) and *Putsay* (1980) calculated the error of several Volz type sunphotometers as a function of the aerosol optical thickness. *Major* (1980) calculated spectrally integrated radiances for a few scattering angles, but did not calculate the circumsolar irradiance. *Thomalla et al.* (1983) investigated both the spectrally integrated circumsolar radiances and irradiances for various atmospheric conditions. Their conclusion is that a field of view larger than the angular size of the sun gives rise to a significant increase in the total (solar plus circumsolar) irradiance only if a thin cirrus layer is present.

In this paper the results of calculations for the circumsolar radiation for various aerosol types are presented. Effects of the variability within the aerosol types are also discussed. Both the circumsolar radiance and irradiance were calculated for the following aerosol models: two maritime type, two urban type, two background type, and a mountain type aerosol models. The results are integrated over the whole solar spectrum region.

2. Method

The circumsolar radiances were calculated for a horizontally homogeneous atmosphere. The spectral absorption and scattering processes were taken into account, but the multiple scattering effects were neglected. This approximation is justified in the forward scattering region (*Thomalla et al.*, 1983). The spectral radiance L_λ can be determined from the solution of the radiative transfer equation. The radiative transfer equation is described in a (θ,φ) polar coordinate system where θ is the angular distance from the sun's center and φ is the azimuth angle. Assuming the sun as a point source, the solution of the radiative transfer at a given wavelength λ is:

$$L_\lambda(\theta,m) = F_{o_\lambda} \exp(-\delta_{o_\lambda} M) \left[P_{m\lambda}(\theta)\,\delta_{msc\lambda} + P_{a\lambda}(\theta)\,\delta_{asc\lambda}\right] \tilde{\omega}_\lambda \times \frac{m}{M-m}\left[\exp(-\delta_\lambda m) - \exp(-\delta_\lambda M)\right], \quad (1)$$

where F_o is the incident solar irradiance at the top of the atmosphere, $\tilde{\omega}_\lambda$ is the single scattering albedo, $P_m(\theta)$ and $P_a(\theta)$ are the phase functions at scattering angle θ for the molecules and for the aerosol particles, respectively. δ_o, δ_{msc}, δ_{asc} are the absorption coefficient of ozone, and the scattering coefficients of molecules and aerosol particles, respectively. δ_λ is the extinction coefficient of the subozone layer, which is the sum of the scattering coefficients of air molecules (δ_m), the extinction coefficient of aerosol particles (δ_a), and the absorption coefficient of H_2O. M and m are the relative air masses in the direction of the sun and in the viewing direction, respectively.

The scattering by air molecules is described by the Rayleigh theory. The scattering of the aerosol particles is calculated by Mie theory and depends on their size distribution and refractive index.

In our calculation the sun is assumed to be a point source. This approximation is very good for a scattering angle greater than about 1 degree (*Grassl*, 1971).

To get the integral radiance of the circumsolar radiation at a distance θ, Eq. (1) is integrated over the wavelength:

$$L(\theta, m) = \int_0^\infty L_\lambda(\theta, m)\, d\lambda . \tag{2}$$

The integration was performed from $\lambda = 0.3\ \mu$m through $\lambda = 4.0\ \mu$m.

The circumsolar irradiance $E_{sc}(\theta)$ is the irradiance on an area normal to the sun direction up to angular distance θ from the center of the sun. $E_{sc}(\theta)$ results from the integration of the radiance $L(\theta,m)$ over the corresponding solid angle:

$$E_{sc}(\theta) = \int_0^{2\pi} \int_0^{\theta} L(\theta', m(\theta', \varphi)) \cos\theta' \sin\theta' \, d\theta' \, d\varphi . \tag{3}$$

The irradiance from the attenuated direct solar flux over the total solar spectrum is given by

$$E_{sun} = \int_0^\infty F_\lambda \exp(-(\delta_\lambda + \delta_{o\lambda}) M)\, d\lambda . \tag{4}$$

The total irradiance $E(\theta)$ is the sum of Eqs. (3) and (4):

$$E(\theta) = E_{sun} + E_{sc}(\theta) . \tag{5}$$

The coefficients δ and the phase functions P necessary to evaluate the above expressions, can be calculated using atmospheric models.

3. *Model atmospheres*

The atmosphere is assumed to be horizontally homogeneous. Molecular scattering, water vapour and ozone absorption, aerosol scattering and absorption are taken into account. It is supposed that there is no cirrus cloud in front of the sun.

The calculations were performed for two groups of aerosol models:

(1) The first aerosol model group contains three models from the well-known Standard Radiation Atmosphere (SRA): CONT-I, MAR-I and URBAN. The full description of these models can be found in Refs. (*Deepak* and *Gerber*, 1983; *WCRP-112*, 1986).

(2) The other group contains models based on aerosol size distributions measured by Hungarian scientists (*Major*, 1980; *Mészáros* and *Vissy*, 1974). These aerosol models represent continental background (B), urban (U), oceanic (O) and mountain (M) aerosol distributions. The background and the urban type aerosol size distributions were measured in Hungary, the mountain type aerosol size distribution was measured in Caucasus in USSR, and the oceanic type on the Indian Ocean (*Mészáros* and *Vissy*, 1974). The size distributions of the dry aerosol particles was approximated by the following equation:

$$\frac{1}{N_o}\frac{dN}{dr} = \sum_{i=1}^{n} a_i \exp\left[-b_i(\log r + c_i)^2\right]. \tag{6}$$

Table 1 shows the coefficients of Eq. (6) and other characteristics of the atmospheric models (*Major*, 1980). The coefficients of the dry aerosol size distribution functions according to Eq. (6) are listed in the first five lines. $\tilde{m}$ is the complex refractive index of the aerosol particles, N_o is the total number of particles in the atmospheric column of 1 μm^2 cross section, the humid particles are x times larger than the dry ones, RH is the relative humidity and p is the surface pressure.

Fig. 1 shows the size distributions of the humid particles of the second group of aerosol models. The increase of the size of the humid particles was taken from *Hänel* and *Bullrich* (1978). All atmospheric models have fixed but different aerosol load. The aerosol optical depths for all aerosol models are tabulated in *Table 2*.

4. *Results*

The results of our investigations are presented in two stages:

(1) In part 4.1 the function $L(\theta)$ is discussed. $L(\theta)$ represents the averaged radiance around the sun at a given angular distance θ:

$$\bar{L}(\theta) = \frac{1}{2\pi}\int_0^{2\pi} L(\theta, m(\theta,\varphi))\, d\varphi . \tag{7}$$

The results can be used to estimate the differences between the circumsolar radiations measured by two pyrheliometers with different geometry. If the global irradiance is measured by the direct-diffuse method (*WCRP-64,* 1991) there is a difference between the pyrheliometer measured and the diffusometer excluded circumsolar radiations. The above results can be useful to estimate these differences.

(2) In part 4.2 we discuss the ratio of the circumsolar irradiance E_{sc} to the direct solar irradiance E_{sun}. The results are mainly of interest for the calculation of optimum receiver apertures of solar power plants.

Table 1. The parameters characterizing the atmosphere models *M* (mountain), *B* (background), U (urban) and O (oceanic)

Models	M	B	U	O
n	4	4	4	3
a, b, c	53, 12, 1.8	24, 9.1, 1.8	36, 9.7, 1.8	12, 24, 1.25
a, b, c	16, 44, 1.25	9.5, 17, 1.25	7.9, 27, 1.25	4.9, 28, 0.94
a, b, c	5, 18, 1.0	1.9, 50, 0.83	2.2, 14, 0.96	0.1, 2.85, 1.00
a, b, c	0.05, 4.5, 0.7	0.13, 3.7, 1.00	0.015, 4.8, 0.7	
N_0 (μm)	0.52	1.9	3.94	0.095
$\tilde{m}$	1.48-0.01i	1.46-0.04i	1.46-0.08i	1.36-0.005i
x	1.02	1.066	1.16	1.7
RH (%)	40	65	56	85
p (hPa)	911	1013.2	1013.2	1013.2

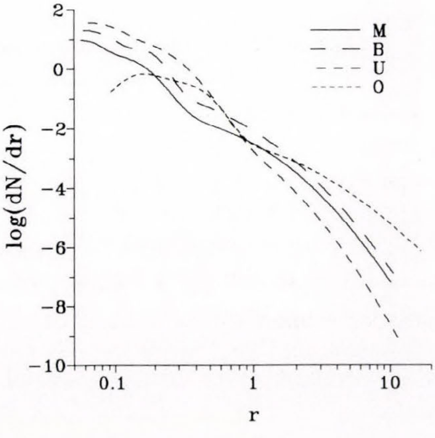


Fig. 1. Size distribution functions of humid particles for the U (urban), B (background), M (mountain) and O (oceanic) models.

Table 2. The aerosol optical depth τ (at $\lambda = 0.55\ \mu m$), the direct solar irradiance E_{sun} and the ratio of the circumsolar to the direct solar irradiances $E_{sc}(\theta)/E_{sun}$ for different model atmospheres for a few θ values and for three sun elevations h. θ is the angular distance from the center of the sun

Aerosol model	τ	h	E_{sun} ($W\ m^{-2}$)	$E_{sc}(\theta)/E_{sun}$ (%)			
				θ			
				2°	5°	7°	10°
O	0.05	60°	921	0.6	1.1	1.3	1.7
		45°	857	0.7	1.3	1.6	2.1
		20°	596	1.4	2.8	3.4	4.3
MAR-I	0.08	60°	893	0.5	1.1	1.5	2.0
		45°	825	0.6	1.4	1.8	2.5
		20°	550	1.2	2.9	3.8	5.2
M	0.07	60°	1000	0.3	0.9	1.2	1.7
		45°	940	0.4	1.1	1.5	2.1
		20°	677	0.7	2.2	3.1	4.3
B	0.19	60°	854	0.6	1.8	2.5	3.5
		45°	777	0.7	2.2	3.1	4.3
		20°	468	1.4	4.4	6.3	8.9
CONT-I	0.23	60°	846	0.5	1.0	1.5	2.2
		45°	768	0.6	1.3	1.8	2.7
		20°	459	1.2	2.5	3.6	5.3
U	0.4	60°	713	0.8	2.3	3.4	5.0
		45°	623	0.9	2.8	4.1	6.0
		20°	299	1.8	5.6	8.2	11.8
URBAN	1.03	60°	469	0.4	1.3	2.2	3.8
		45°	380	0.5	1.5	2.5	4.4
		20°	126	0.8	2.5	4.1	7.0

4.1 Radiance of the circumsolar radiation

The aerosol particles scatter mainly forward, so the circumsolar radiation decreases strongly with increasing angular distance from the sun.

In *Fig. 2a–d* the averaged radiance $\bar{L}(\theta)$ is plotted as a function of the angular distance θ from the sun's center for different aerosol types and for three different sun elevation angles. Fig. 2a–c presents curves for two related aerosol models: one of the SRA models and one of the measured aerosol models. On Fig. 2d the results for the M model are shown, which has no SRA counterpart. The aerosol optical depths at $\lambda = 0.55\ \mu m$ are indicated on the figures. For the sake of comparison, the same optical depths were taken for the related aerosol models.

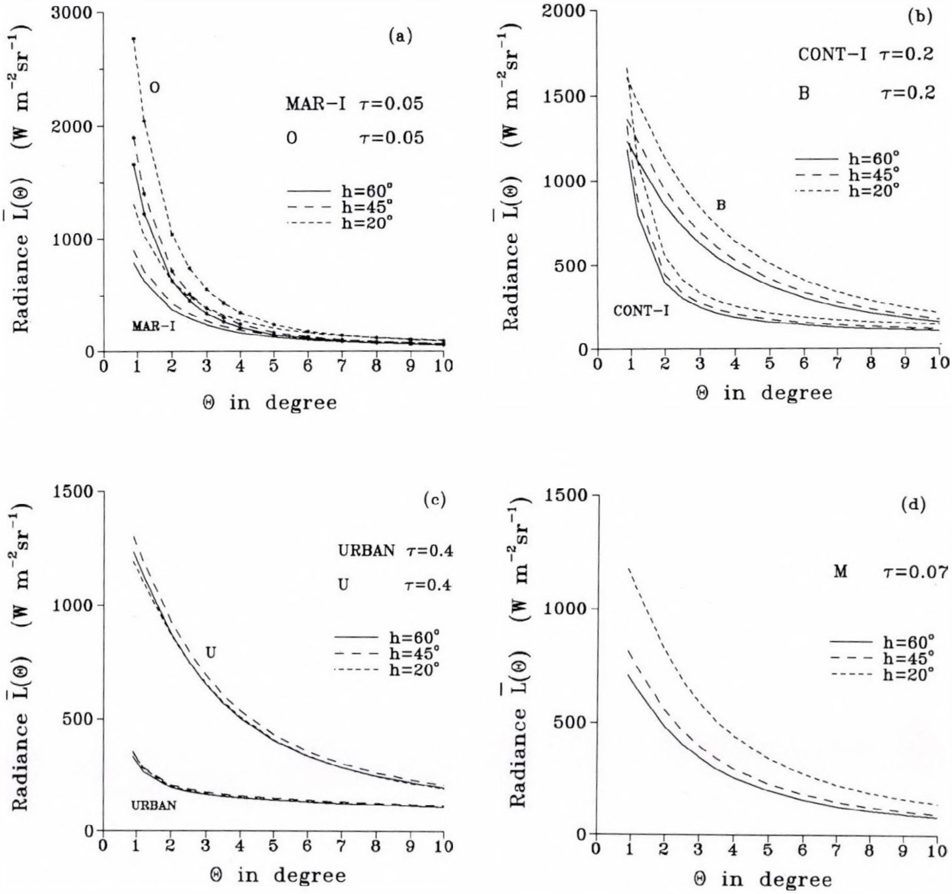


Fig. 2. Radiance $\bar{L}(\theta)$ for aerosol models *(a)* O and MAR-I, *(b)* B and CONT-I, *(c)* U and URBAN, *(d)* M. (Averaged around the sun at the θ angular distance. In each case with three different values of sun elevation h. The τ values given are the aerosol optical depths at wavelength $\lambda = 0.55\ \mu m$.)

The radiance curves of aerosol models with relatively more large particles show a stronger decrease than those of aerosol models with relatively less large particles. As a result the curves in Fig. 2a (model O and MAR-I) have the steepest slope, and the URBAN aerosol in Fig. 2c has the shallowest one. These two aerosol models represent extreme cases of atmospheric aerosol concerning size distribution, model O with high proportion of large particles, model URBAN of SRA with a high proportion of small particles.

The models O and MAR-I are very close to each other (see Fig. 2a). The curves of the model O are a little higher than those of model MAR-I. Fig. 2b shows the results for the models B and CONT-I. The curve of model CONT-I is the steepest, because it contains more large particles. Fig. 2c shows the curves for the model URBAN of SRA and for the model U measured in Hungary. One can see that the results differ significantly. The reason of this difference could be that the measurements were made at the border of Budapest, where the aerosol size distribution is not really of a typical urban type, rather a mixture of urban and background types. As a consequence model U contains relatively more large particles. Model URBAN of SRA contains much more small particles. Fig. 2d shows the curve for the mountain (M) model. The values are relatively small because of the low aerosol optical depth and the low relative humidity.

In the case of low optical depths (see Fig. 2a–b, and 2d) the circumsolar radiance increases with decreasing sun elevation. In the case of high optical depths, however, this behaviour changes (Fig. 2c). The reason is simple. If the radiation beam meets more particles on its path through the atmosphere, then more photons scatter, but the extinction of the scattering radiation is also higher.

We have also investigated the dependence of the circumsolar radiation upon the aerosol optical depth for each model. In general, with increasing aerosol optical depth the radiance first increases and then decreases. The angular distribution of the circumsolar radiance function is determined by the aerosol size distribution, while the height of the $\bar{L}(\theta)$ curves depends mainly on the air mass (which depends on the sun's elevation) and the aerosol optical depth.

4.2 Ratio of circumsolar to direct solar irradiance

The ratio of the circumsolar to the direct solar irradiance ($E_{sc}(\theta)/E_{sun}$) gives information about the circumsolar radiation involved into the pyrheliometric measurements. *Fig. 3* shows the ratio of the circumsolar to the direct solar irradiance as a function of the angular distance θ for various model atmospheres. The aerosol optical depths tabulated in Table 2 were used. The sun elevation was h = 45°. The same ratios for three different sun elevations and the corresponding direct solar irradiance in W m^{-2} are tabulated in Table 2 for a few θ values. Since measurements are usually carried out only if E > 400–500 W m^{-2}, and the most frequently used pyrheliometer have a field of view of 4–6 degree, the circumsolar contribution to the pyrheliometric measurements is less than 5%, mostly about 2%.

We have also investigated the dependence of the circumsolar radiation upon the aerosol optical depth. We calculated the ratios of circumsolar to direct solar irradiance for the seven atmosphere models varying the aerosol optical depth (see *Fig. 4*). The ratio at 5° is less than 5% in most of the cases. This percentage may be higher for greater values of optical depth and for low sun elevation, but in this cases the attenuation of the direct sun radiation is so great that the absolute increase is still small. Furthermore, in the case of low direct irradiance, pyrheliometric measurements are usually not carried out.

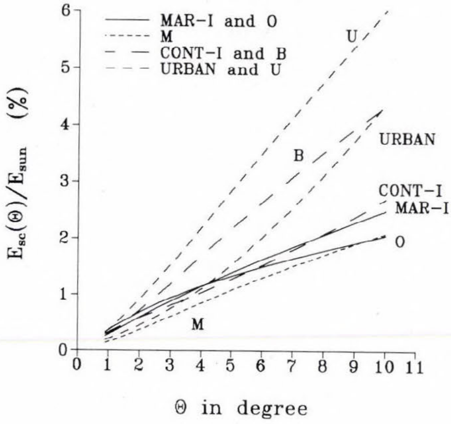


Fig. 3. The ratio of the circumsolar to the direct solar irradiance for seven aerosol models as a function of θ. The sun elevation is h = 45°.

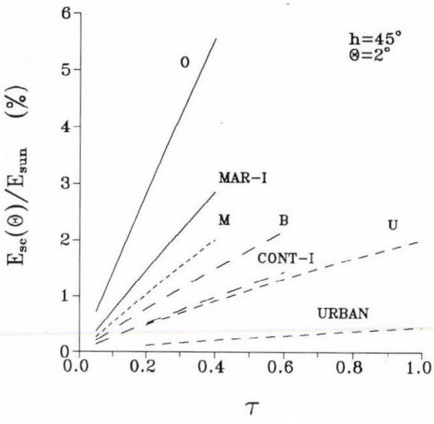


Fig. 4. The ratio of the circumsolar to the direct solar irradiance for seven aerosol models at $\theta = 2°$ for sun elevation $h = 45°$ as a function of the aerosol optical depth τ at $\lambda = 0.55\ \mu m$.

5. Conclusion

We have calculated the variation of the circumsolar radiance and irradiance taking into account the relevant optical parameters: extinction and scattering of the solar radiation by molecules and aerosol particles, absorption by gases, and different elevation angles of the sun.

The calculations have been carried out for seven different aerosol models which belong to four aerosol types (maritime, urban, background and mountain). We have compared the radiances of the related model pairs. We have found that the circumsolar radiance functions $L(\theta,m)$ were very close to each other for the two maritime type aerosol models. The difference was greater for the two continental background type models, but still not significant. However, the circumsolar radiance functions for the two urban type models showed a significant difference due to the different aerosol size distributions and the optical depths of these models.

In general, the angular distribution of the circumsolar radiance function is determined by the aerosol size distribution, while the height of the $\bar{L}(\theta)$ curves depends mainly on the relative air mass (which depends on the sun's elevation) and the aerosol optical depth. The radiance curves of aerosol models with a greater proportion of large particles show a stronger decrease than those of aerosol models with a lower proportion of large particles. We have also investigated the influence of the optical depth. We have found that for a given model with increasing aerosol optical depth the radiance first increases and then decreases. The effect of the sun elevation on the circumsolar radiance depends strongly on the aerosol optical depth. For low optical depths the circumsolar radiance increases with decreasing sun elevation, for high optical depths it decreases, and for medium optical depth it shows a maximum.

The ratio of the circumsolar to the direct solar irradiance was calculated for different sun elevations, angular distances, aerosol optical depths and aerosol models. If the direct solar irradiance is greater than 500 W m^{-2} (i.e. under good measuring conditions) then the ratio is less than 5%, mostly about 2% at a field of view of 5°. The ratio can be higher for greater values of optical depth and for low sun elevation, but in these case the attenuation of the direct solar radiation is so great that the absolute value of the circumsolar irradiance is still small.

References

Deepak, A. and *Gerber, H.E.*, (eds.), 1983: Report of the experts meeting on aerosols and their climatic effects. *World Climate Research Programme, WCRP-55.*

Eiden, R., 1968: Calculations and measurements of the spectral radiance of the solar aureole. *Tellus 20*, 380-398.

Fröhlich, C. and *Quenzel, H.*, 1974: Influence of the sun's aureole on the determination of turbidity. *Special Environmental Report No. 3, WMO-No. 368*, 538-544.

Grassl, H., 1971: Calculated circumsolar radiation as a function of aerosol type, field of view, wavelength, and optical depth. *Applied Optics 10*, 2542-2543.

Green, A.E.S., Deepak, A. and *Lipofsky, B.J.*, 1971: Interpretation of the sun's aureole based on atmospheric aerosol models. *Applied Optics 10*, 1263-1279.

Hänel, G. and *Bullrich, K.*, 1978: Physico-chemical property models of tropospheric aerosol particles. *Contrib. Atm. Phys. 51*, 129-138.

Major, G., 1980: A method for determining the circumsolar sky function. *Tellus 32*, 340-347.

Major, G., 1992: Estimation of the error caused by the circumsolar radiation when measuring global radiation as a sum of direct and diffuse radiation, *Solar Energy 48*, 249-252.

Mészáros, A. and *Vissy, K.*, 1974: Concentrations, size distribution and chemical nature of atmospheric aerosol particles in remote oceanic areas. *Journal of Aerosol Sciences 5*, 101-109.

Putsay, M., 1980: The effect of circumsolar radiation on accuracy of turbidity measurements. *Időjárás 84*, 261-267.

Thomalla, E., Köpke, P., Müller, H. and *Quenzel, H.*, 1983: Circumsolar radiation calculated for various atmospheric conditions. *Solar Energy 30*, 575-587.

WCRP-112, 1986: A preliminary cloudless standard atmosphere for radiation computation. *World Climate Research Programme, WCRP-112, WMO/TD No. 24.*

WCRP-64, 1991: Radiation and climate. Second Workshop on Implementation of the Baseline Surface Radiation Network. *WMO WCRP-64.*

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 2, April–June 1995

The role of geometry in the comparison of standard pyrheliometers

G. Major

Hungarian Meteorological Service,
P.O. Box 39, H-1675 Budapest, Hungary

(Manuscript received 16 February 1995; in final form 10 April 1995)

Abstract—The recently valid pyrheliometric scale (World Radiometric Reference) is based on cavity pyrheliometers. The geometrical characteristics of these cavity instruments are closer to each other than those of pyrheliometers manufactured earlier. Some of the Regional and National Standard Pyrheliometers are different types of Ångström pyrheliometers, their geometry differ significantly from that of the cavity ones and from each other. Using different distributions of scattering aerosol, calculations have been made for determining the difference of the circumsolar radiation measured by the standard pyrheliometers altogether with the actual direct radiation. The geometrical factor, necessary to calculate the longwave radiation exchange between the pyrheliometric sensor and the outer environment, has also been derived. The results show that in the case of high precision comparison of standard pyrheliometers the circumsolar effect is of the same order as the reliability of the comparison.

Key-words: pyrheliometer, circumsolar radiation, pyrheliometric IR loss.

1. Introduction

In 1977 the World Meteorological Organization changed its Technical Regulations (*WMO*, 1977): after 1 January 1981 all pyrheliometric measurements should be expressed in the scale of the World Radiometric Reference (WRR). This change affects all solar radiation measurements, since in the meteorological radiometry the pyrheliometers are the only absolute instruments. The WRR is maintained by a group of selected cavity pyrheliometers.

Most of the existing cavity pyrheliometers have been designed after 1970. Previous types of pyrheliometers were significantly different in respect of geometry. The different view limiting geometry results in different contribution of the circumsolar radiation measured altogether with the actual direct radiation.

Hence the instrument outputs could not been precisely compared. The geometry of different cavity pyrheliometers is more uniform than that of the older pyrheliometers. The International Pyrheliometer Comparisons have proved that the ratio of the measurements of cavity pyrheliometers has the precision of 10^{-4}. Regarding this high precision of comparability, all factors have to be taken into account that might affect the ratio of the measurements of pyrheliometers.

In this paper the effect of view limiting geometry is analyzed regarding the circumsolar irradiation and the longwave radiation exchange of the pyrheliometric sensors. Not only the cavity type instruments are taken into account but also the other standard pyrheliometers that took part in the last International Pyrheliometer Comparison in 1990.

2. *Method*

In this work the geometry of pyrheliometers is described by their penumbra function (the derivation is shown in *Pastiels*, 1959 or *Major*, 1994). The effective penumbra function, $F(z,\varphi)$, gives that part (fraction) of the receiver surface, weighted by the sensitivity, that can be seen from the (z,φ) direction. Here z is the angle between the optical axis of the pyrheliometer and the viewing direction, φ is the azimuth angle of the direction in a plane perpendicular to the optical axis. The geometrical penumbra function, $G(z,\varphi)$, gives the fraction of the receiver surface that can be seen from the (z,φ) direction. If the receiver has uniform sensitivity along its surface, the two functions are identical.

In the case of cavity pyrheliometers the entrance of the cavity is regarded as receiver surface. According to the physical nature of the cavity, this 'receiver surface' has uniform sensitivity distribution. Moreover, these pyrheliometers have rotational symmetry around their optical axis. Therefore, the penumbra values do not depend on the azimuth, so that the geometry of the cavity pyrheliometers is fully described by the geometrical penumbra function $G(z)$. In the case of circular pyrheliometers, having the radius of the entrance aperture (R), the radius of the receiver (r) and the tube length (L, the distance between them), the geometrical penumbra values can be calculated by an analytical form (*Pastiels*, 1959).

In the case of Ångström pyrheliometers and NIP (the Eppley factory made Normal Incidence Pyrheliometer) the sensitivity is not uniform along their sensing surface. The ouput of these instruments is connected with their effective penumbra function. This function was derived by numerical simulation (*Major*, 1994) for different types of Ångström pyrheliometers taking into account the calculated sensitivity distribution (*Major*, 1968) derived from the 'analog' procedure suggested by *Pastiels* (1959).

To calculate the difference of the circumsolar radiation involved in the outputs of different pyrheliometers, the radiance distribution has to be known along the circumsolar sky. These functions were calculated by *Putsay* (1995) using different aerosol models.

To calculate the longwave radiation exchange between the receiver and the environment outside of the pyrheliometer let us define the following ratio:

$$\psi = \frac{\text{irradiation received through the aperture}}{\text{irradiation received from the hemisphere}}.$$

This ratio can be calculated if the radiance distribution is isotropic. It can be shown easily, that for a pyrheliometer

$$\psi = \int_0^{z_1} F(z) \sin(2z)\, dz .$$

Here z_1 is the limit angle of the pyrheliometer. This is the largest angle from the optical axis from which the receiver can be seen at all. For the circular case $z_1 = \text{atn}\ ((R + r)/L)$.

The assumed isotropy does not limit the applicability of this ratio, since within the field of view of a pyrheliometer the atmospheric infrared radiation is almost isotropic at any elevation angle.

If the pyrheliometer has a receiver with uniform sensitivity and a circular structure, the ψ value can easily be calculated using *Pastiels*' (1959) theorem:

$$\psi = (a^2 + b^2 + 1) - \sqrt{(a^2 + b^2 + 1)^2 - 4a^2}\ ,$$

here $a = R/r$ and $b = L/r$.

3. *Basic geometric data*

Table 1 is taken from the report of the *IPC VII* (1991). It contains the basic geometric data of the different types of standard pyrheliometers which took part in that comparison.

The given sizes do not characterize directly the viewing angles, therefore in *Table 2* the characteristic angles are shown for the circular pyrheliometers. The slope angle (z_s) is the largest angle between the optical axis and the direction from that the full receiver can be seen. In the circular case $z_s = \text{atn}\ ((R - r)/L)$.

Table 1. The basic geometrical data of cavity, NIP and Ångström pyrheliometers taken part in the 1990 International Pyrheliometer Comparisons. (Here v is the length, w is the width of the entrance aperture of Ångström pyrheliometers.)

Instrument	R (mm)	r (mm)	L (mm)
Cavity			
PMO2	3.6	2.5	85.0
PMO5	3.7	2.5	95.4
CROM 2L	6.29	4.999	144.05
CROM 3L	6.25	5.0	144.0
PAC 3	8.18	5.64	190.5
HF 18748	5.81	3.99	134.7
MKVI 67814	8.2	5.65	187.6
PMO6generic	4.1	2.5	94.0
PMO6-5	3.6	2.5	84.2
PMO6-10	4.25	2.5	95.4
EPACgeneric	8.32	5.64	190.5
HFgeneric	5.81	3.99	134.7
MKVIgeneric	8.2	5.65	187.6
MKVI 67401	8.2	5.64	190.5
PCC3-005	10.0	5.0	114.5
Thermopile			
NIP 18653	10.3	4.0	203.0
Ångström	v (mm)	w (mm)	
A-7	9.5	7.5	150.0
A-171	10.25	2.4	72.2
A-212	11.8	2.5	50.0
A-559	10.0	8.0	70.0
A-564	10.3	2.5	75.1
A-568	10.6	4.0	55.5
A-576	10.0	2.5	82.0
A-578	10.3	2.5	70.5
A-Eppley	10.3	4.1	111.0

The PCC3 differs much from the other cavity instruments. A bolometric pyrheliometer constructed by Sklyrov had similar geometry (*Voytyuk* and *Sklyrov*, 1973). It is an experimental version, which is not available commercially. The limit angles of the other standard pyrheliometers are relatively similar to each other. The CROM 3L has the smallest, the PMO6–10 has the largest slope angle. The remaining devices are quite similar, so their group will be represented in this paper by a symbolic absolute instrument ABS (R = 8.2 mm, r = 5.7 mm, L = 191 mm). Similarly, the Ångström pyrheliometers have been grouped into 4 symbolic instruments: Eppley Ångström (EPA), Smithsonian Ångström (SMA), Short Tube Ångström (SHA) and Modern Ångström (MOA).

Table 2. Characteristic angles of the circular pyrheliometers taken part in the 1990 International Pyrheliometer Comparisons

Instrument	Slope angle (deg)	Limit angle (deg)
PMO2	0.74	4.10
PMO5	0.72	3.72
CROM 2L	0.51	4.48
CROM 3L	0.50	4.47
PAC 3	0.76	4.15
HF 18748	0.78	4.16
MKVI 67814	0.78	4.22
PMO6generic	0.98	4.02
PMO-5	0.75	4.14
PMO6-10	1.05	4.05
EPACgeneric	0.81	4.19
HFgeneric	0.77	4.16
MKVIgeneric	0.78	4.22
MKVI 67401	0.77	4.16
PCC3-005	2.50	7.46
NIP 18653	1.78	4.03

Table 3 contains the effective penumbra functions for the above mentioned pyrheliometers.

Table 3. Effective penumbra functions of the representative standard pyrheliometers

z (deg)	ABS	CRO3	PMO6	PCC	EPA	SMA	SHA	MOA
0	1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00
1	0.95	0.88	1.00	1.00	0.92	0.96	1.00	0.99
1.5	0.78	0.72	0.87	1.00	0.60	0.62	1.00	0.92
2	0.59	0.56	0.67	1.00	0.29	0.22	1.00	0.85
2.5	0.41	0.41	0.46	1.00	0.03	-0.04	0.99	0.69
3	0.25	0.27	0.26	0.93	-0.04	-0.12	0.96	0.53
3.5	0.11	0.15	0.10	0.82	-0.09	-0.19	0.91	0.42
4	0.01	0.05	0.03	0.73	-0.13	-0.23	0.85	0.30
6	0	0	0	0.21	-0.12	-0.01	0.33	-0.06
8	0	0	0	0	-0.03	0	-0.01	-0.15
10	0	0	0	0	-0.01	0	-0.09	-0.07
15	0	0	0	0	0	0	-0.06	-0.02

The Ångström pyrheliometers have negative penumbra values at some angles. This means that their shaded strip area is larger than the open strip area seen from that angle.

4. The sky functions

The model atmospheres are plan-parallel and cloudfree. Molecular scattering, water vapour and ozone absorption, as well as aerosol scattering and absorption are taken into account. The calculations were made for two groups of aerosol distribution. The first group contains three models of the Standard Radiation Atmosphere (*WCRP*, 1986): continental (CONT), maritime (MAR), and URBAN. The second group contains four models, described by *Major* (1980): continental background (B), urban (U), oceanic (O) and mountain (M) aerosol. The two urban models are similar to each other in having high turbidity values, but they differ in the size distribution.

The details of the calculation are described by *Putsay* (1995). In this work only those results are used that refer to optical depths typical for the given aerosol and to solar elevation angles of 20, 45 and 60 degrees.

5. Calculated circum differences

Using the sky functions derived for the mentioned aerosol models, differences of circumsolar radiation between the representative pyrheliometers and the ABS have been calculated (see *Table 4*). Applying the penumbra functions, the following formula served this purpose (shown the CROM as example):

$$C_{CROM-ABS} = \pi \int_0^{z_1} \left[F(z)_{CROM} - F(z)_{ABS} \right] \sin(2z)\, dz .$$

As it is expected (knowing the characteristic angles and the penumbra functions), the CROM 3L measures less, the PMO6–10 measures more circumsolar radiation than the ABS. The difference is less than 0.5 W m^{-2}, but it is of the order of 10^{-4}. The World Standard Group of cavity pyrheliometers defining the World Radiometric Reference ought to avoid such possibility of disturbance.

The PCC instrument has to be reconstructed from the point of geometry. The deviation of the different Ångström type instruments is of the order of 10^{-3}.

6. The infrared radiation exchange

The thermal environment of a pyrheliometer receiver is homogeneous except the open aperture hole. The infrared or longwave radiation energy exchange through the aperture can be calculated using the forementioned ψ factor:

$$IR = \psi \sigma \left[(T_r)^4 - (T_e)^4 \right],$$

where T_r is the temperature of the receiver, T_e is the effective environmental temperature outside of the pyrheliometer.

Table 4. The difference between the circumsolar radiation measured by the pyrheliometers named in the left column and the ABS. The values are in W m^{-2} for 20, 45 and 60 degrees of solar elevation angle

	O	M	MAR	B	CONT	U	URBAN
CROM	-0.21	-0.04	-0.11	-0.01	-0.11	-0.01	0
	-0.15	-0.03	-0.08	-0.01	-0.09	0	0
	-0.13	-0.03	-0.07	-0.01	-0.08	-0.01	-0.01
PMO	0.54	0.34	0.46	0.50	0.32	0.33	0.07
	0.37	0.24	0.33	0.41	0.27	0.49	0.12
	0.32	0.21	0.29	0.37	0.23	0.50	0.12
PCC	5.53	4.86	5.68	7.88	3.73	5.47	1.12
	3.82	3.28	4.06	6.40	3.12	7.97	2.02
	3.35	2.84	3.56	5.74	2.82	7.94	2.14
EPA	-2.44	-1.96	-2.36	-3.09	-1.56	-2.12	-0.42
	-1.68	-1.32	-1.69	-2.51	-1.30	-3.11	-0.76
	-1.47	-1.14	-1.49	-1.26	-1.18	-3.10	-0.81
SMA	-2.70	-2.29	-2.71	-3.68	-1.76	-2.55	-0.51
	-1.87	-1.55	-1.94	-2.99	-1.47	-3.71	-0.92
	-1.63	-1.35	-1.70	-2.68	-1.33	-3.70	-0.97
SHA	4.42	3.91	4.55	6.36	3.31	4.43	0.90
	3.05	2.63	3.36	5.17	2.51	6.44	1.64
	2.67	2.29	2.86	4.64	2.28	6.43	1.74
MOA	1.98	1.66	1.97	2.66	1.31	1.84	0.37
	1.36	1.12	1.41	2.16	1.10	2.69	0.67
	1.19	0.98	1.24	1.95	1.39	2.69	0.71

Table 5 contains values of ψ factor for some cavity pyrheliometers altogether with some examples of the infrared energy loss. Except the PCC instrument, the atmospheric infrared energy loss is almost the same for the other standard pyrheliometers. The difference remains negligible even in the hypothetical case of looking into the deep space (T_e = 0) through an open aperture.

Table 5. The IR exchange factor (ψ) and energy loss values (W m^{-2}) for some pyrheliometers. The receiver temperature is 300 K

Instrument	ψ	T_e = 290	T_e = 280	T_e = 270	T_e = 0
ABS	0.00184	0.11	0.20	0.29	0.85
PMO6-10	0.00198	0.12	0.22	0.31	0.91
CROM 3L	0.00188	0.11	0.21	0.30	0.87
PCC	0.00756	0.44	0.84	1.20	3.49

7. Conclusions

The latest development in pyrheliometry, the appearance of cavity instruments, has led to the definition a much more precise pyrheliometric scale than the previous one, but the problem of different geometry has not been eliminated fully, since the effect of circumsolar radiation is of the same order as the comparability (10^{-4}) of this instruments.

The WRR scale would be transferred more reliably if all the Regional and National Standard Pyrheliometers would be cavity instruments, since the circumsolar effect of other type pyrheliometers is of the order of 10^{-3}.

The infrared energy loss of most of the cavity pyrheliometers is quite similar. In the case of extreme geometry it should be taken into account.

References

IPC VII, 1991: International Pyrheliometer Comparisons, 24 September–12 October 1990. *Working Report* No. 162, Swiss Meteorological Institute.

Major, G., 1968: Distribution of sensitivity along the sensors of pyrheliometers. *Időjárás 72,* 351-362.

Major, G., 1980: Method for determining the circumsolar sky function. *Tellus 32,* 340-347.

Major, G., 1994: Circumsolar correction for pyrheliometers and diffusometers. *WMO/TD* No. 635.

Pastiels, R., 1959: Contribution a l'étude du probleme des méthodes actinométriques. *Publications, Série A,* No. 11. Inst. Royal Mét. de Belgique.

Putsay, M., 1995: Circumsolar radiation calculations for various aerosol models. *Időjárás 99,* 67-76.

Voytyuk, Y.V. and *Sklyrov Y.A.*, 1973: Calculation of error of bolometric pyrheliometer. Part IV. *Studies in Climate and Weather*. University of Saratov, 1/8, 142-151.

WCRP, 1986: A Preliminary Cloudless Standard Atmosphere for Radiation Computations. *WCRP-112, WMO/TD* No. 24.

WMO, 1977: CIMO Abridged Final Report of the Seventh Session. Geneva.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 2, April–June 1995

Variation of daily extreme temperatures in Hungary

Zsuzsanna Iványi

Department of Meteorology, Eötvös Loránd University,
Ludovika tér 2, H-1083 Budapest, Hungary

(Manuscript received 17 February 1994; in final form 31 March 1995)

Abstract—Six Hungarian meteorological stations were used to investigate the variation of daily maximum and minimum temperatures for the period 1901–1990. In the initial phase of the survey linear trend analysis was applied. In this paper results of the analysis are presented and discussed. Significant trend was found only in a very few cases. No significant increasing or decreasing change can be stated for the daily extreme temperatures based on stationary data. Suggestions are made for the further analysis.

Key-words: climate change, daily extreme temperature, trend analysis, Hungary.

1. Introduction

The increase of the concentration of the greenhouse gases in the atmosphere might result in an increase of the global average temperature, as well. According to the GCMs it is forecasted that the average temperature will rise by some degrees, if the CO_2 concentration is doubled. However, local temperature series do not seem to confirm this former statement. Namely, according to the measurements the northern hemisphere is presently not warming in a greater extent than the southern. Furthermore, temperature values do not show greater increase in the higher latitudes than in the lower ones (*Ecsedy* and *Murphy*, 1992). It seems to be very probable that — provided, the scenarios produced by GCMs are correct — we have to wait for about 50 years for the realization of temperature increase.

Recently the idea arose that extreme temperature values, better to say their variation might reflect an initial signature of global warming. It means that the meteorological events show more extreme character, namely the changes experienced in relative frequencies and intensity of the extremes might be considered as the first signs of a possible climate change. However, it demands a great caution to draw conclusions for the climate change. *Balling et al.* (1990) have pointed out that rising mean temperatures are associated with changes in the occurrence of extreme minimum temperatures (more days of extreme high minimum temperatures), however they are less related to the occurrence of extreme maximum temperatures.

Concerning the annual and monthly average maximum and minimum temperatures in the northern hemisphere it was experienced in the past 40 years that difference between the maximum and minimum values has been decreased. It is due to the fact that the increase of minimum values is greater than the change of maximum temperatures (*Karl et al.*, 1984). The physical mechanism resulting in the observed changes is still not clear. Among the reasons changes in cloudiness, concentration of aerosols, atmospheric water-content and carbon-dioxid might play an important role. *Karl et al.* (1991) suggest that analyzing minimum temperature series (especially cloudless nights) will best indicate the green-house effect.

Variation of extreme meteorological elements was one of the main issues of 5th International Meeting on Statistical Climatology held in Toronto, Ontario, Canada 22–26 June 1992. Chinese researchers made extensive studies in this field. By using 60 stations variation of daily maximum and minimum temperatures for series of 35 years was investigated. Taking into account of geographical distribution it was found that in Northern-China temperature minima were increasing at a greater rate than the maxima. It should be emphasized that in South-East-China an opposite trend (i.e. decreasing) was experienced. The trend changes according to seasons, as well (*Zhuang* and *Jiliang*, 1992). Warming has been observed mostly in winter and at night (*Zhongwei*, 1992). In the middle part of China the winter temperature has increased in the past 40 years, a peak was found between 1986 and 1991 (*Qun* and *Yiwen*, 1992). A good correlation was obtained between the extent of warming and the CO_2 content of the atmosphere.

In Canada and the United States no warming trend was observed except Western-Canada (*Gan*, 1992). It seems probable that warming or cooling trends have a regional character, both can occur for the same period, but in different areas. Gap between daily maximum and minimum has changed in a small-extent in Finland, as it was shown by *Heino* (1992). During the investigated period minimum temperatures approximately remained constant, but maximum temperatures have decreased to a certain extent. *Karl et al.* (1993) have shown that for over 50% of Northern Hemisphere landmasses minimum temperature increased at a rate three times compared to that of maximum temperature during the period 1951–1990. This change was detected in all seasons and most of the regions studied. *Brázdil et al.* (1994) investigated trends of maximum and minimum daily temperatures in Central and South-Eastern Europe. Using station data for the period of 1951–1990 area averages were calculated for each season and linear trend analyses were carried out. With a few exceptions it was found that no significant trend exists for the seasonal temperature extremes concerning area-averages. It seems reasonable to investigate extreme temperature data experienced in the stations for a long period.

In Hungary about 100 year long temperature-series are available for some stations. The paper was motivated by this fact, namely it seems worthwhile to analyse minimum and maximum temperatures. The question to be investigated is the following: can any trend be seen in the long-term daily maximum and minimum temperatures in Hungarian stations?

2. Database

Before introducing database used for this study, one important issue must be stressed. It is well-known that in urban areas a similar phenomenon can be observed, i.e. at night minimum temperature is higher than over the suburban areas. This is the so called urban heat-island which has been known for a long time. From this fact it can be concluded that when trend of minimum temperature is to be investigated, urban areas must be excluded. Another important issue is whether data available are homogeneous. For the verification of the homogeneity of climatological series cumulative sums of deviations were made by *Craddock* (1979) calculating the differences between the reference station and other stations considered. *Coops* and *Schuurmans* (1986), furthermore *Pettit* (1979) made similar investigations. For summarizing it can be stated that information content of the observed data series should be preserved, namely the applied statistical method may not destroy the original structure of data. Artificial manipulation of the observations, which might lead to the decrease of the information content has to be avoided, because it can result in distortion of estimations. What is the most important for it, to provide the homogeneity of data series in climatological sense.

The purpose of the present study — analysis of the long term series of maximum and minimum temperatures — means a strong restriction for data to be included into the investigation. The homogeneity stressed above is not fulfilled in a clear sense for data available in Hungary, since meteorological station situated outside of towns was not found, which were not moved to another place during the history. After having information about the history of the stations, checking the position and the new circumstances, the following stations were chosen for the study: Mosonmagyaróvár, Szombathely, Kalocsa, Kecskemét, Túrkeve, Nyírergyháza. These meet the following requirements:

- data series are satisfactorily long (it was chosen 90 years),
- stations are situated outside of urban areas,
- stations cover more or less the territory of Hungary.

Database provided by the above mentioned stations were used for the study without any modification or homogenization. No area averages were calculated, because we were interested in it, how surface temperatures measured in individual stations have been changing.

Daily extreme temperature values were considered for the period between 1901 and 1990. A seasonal separation was made, namely extreme temperatures were determined for winter, spring, summer and autumn. For each case absolute and average maximum and minimum values were treated separately. It was supposed that the trend is a linear function of time. For the variation of average and absolute extreme temperatures graphs were made for each season and the trend function was compiled by using the least-square method. Significance of trend was checked by using the *t*-test.

3. Results and discussion

Findings of the investigation are presented to look over data coming from western part of Hungary to the east. Mosonmagyaróvár situated in the north-western part of the country shows no sign of any marked change in any of the seasons. Maximum temperatures show a slight increase with the years, except in summer. Concerning minimum temperatures a slight decrease was found in each season. Similar results were received for Szombathely located at the western border of Hungary. In both stations minimum temperatures seem to decrease to a small extent in every season. For illustrating results the above mentioned variation of extreme temperatures are presented for Mosonmagyar-óvár in winter (*Fig. 1*).

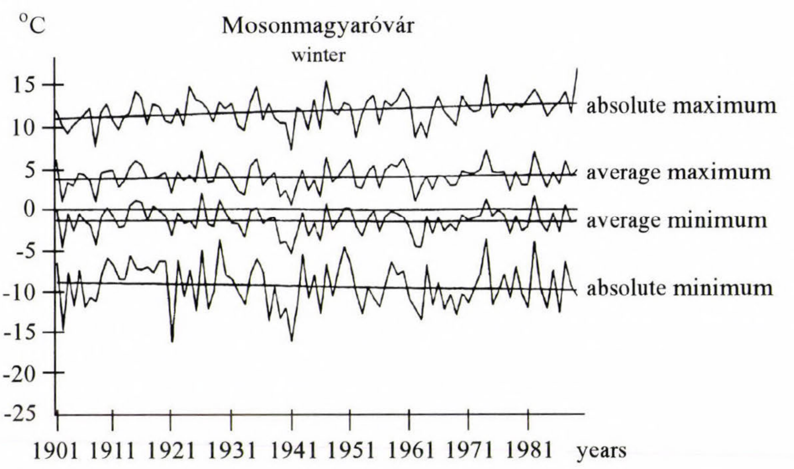


Fig. 1. Variation of extreme temperatures.

Kalocsa represents the middle part of Hungary. Minimum temperatures were decreasing in each season, the rate was highest in summer and autumn. In summer maximum temperatures seemed to be almost constant. It is very interesting that the two other stations, Kecskemét and Túrkeve, which are situated not far from Kalocsa show different tendencies. As regards minimum temperatures, data for Kecskemét seem to be quite steady in winter, but increase in summer. Maxima decrease in summer, but increase in other seasons. In Túrkeve both maximum and minimum temperatures increase, the rate for maximum values is a little bit higher than for the minima except in winter. Till this time no explanation can be given for the difference experienced in the stations situated not far from each other in the central part of Hungary. Further detailed analyses are required for revealing the history of the observations, furthermore homogeneity of the data-series have to be checked. Nyíregyháza located in the eastern part of the country represents a stations having the most continental character. It was found that in summer maximum temperatures decrease, minimum values increase during the period investigated. In winter no essential change was experienced. In spring and autumn slight increase was observed in the past 90 years.

Table 1 shows the rate of variation of temperature extremes quantitatively. Experienced changes of temperature extremes are very different. These results are not in agreement with other experiences, namely maxima are increasing at a smaller rate than minima. In many cases minima decrease, however these are not significant, except one case. Only in a very few cases significant trend was found (Table 1). No conclusion can be drawn concerning diurnal range of temperature, since no significant trend was obtained for both maximum and minimum temperature at any of the stations.

In order to illustrate the test for characterizing statistically the trend, two samples are presented. *Fig. 2a* shows the significantly increasing trend of absolute minimum temperature series found in Nyíregyháza in summer. Remind that no significant trend occurred for the maximum temperatures for the same case. *Fig. 2b* presents the significantly decreasing trend of absolute minimum temperature experienced in Kalocsa in summer. These two figures and the table show, how contradictory results were received. So, no conclusion can be made concerning the direction of temperature extreme experienced in the individual stations in various parts of Hungary. Further investigations are necessary including the following tasks:

- homogeneity of data-series has to be checked statistically,
- analyses is to be carried out for temperature-series averaged for some territories,
- other methods than the linearity of the trend are to be used for the trend-analysis.

Table 1. Linear trends (°C/10 yr) for daily temperature extremes. Significant trends are marked by an asterisk, where $p < 0.05$.

Stations	Absolute maximum	Average maximum	Average minimum	Absolute minimum
Moson-magyaróvár				
Spring	0.06	0.05	-0.02	-0.11
Summer	-0.05	0.01	-0.06	-0.19
Autumn	0.19	0.16	-0.01	-0.09
Winter	0.21	0.06	-0.02	-0.11
Szombathely				
Spring	0.02	0.01	-0.04	-0.13
Summer	-0.02	-0.03	-0.03	-0.15
Autumn	0.24	0.16	-0.04	-0.13
Winter	0.23	0.03	-0.08	-0.11
Kalocsa				
Spring	0.03	0.03	-0.10	-0.16
Summer	-0.11	-0.06	-0.19*	-0.27*
Autumn	0.08	0.11	-0.11	-0.22
Winter	0.02	-0.03	-0.06	-0.12
Kecskemét				
Spring	0.02	0.04	0.11	0.10
Summer	-0.14	-0.06	0.13	0.15
Autumn	0.03	0.09	0.11	0.08
Winter	0.14	0.04	0.06	0.05
Túrkeve				
Spring	0.12	0.08	0.08	-0.01
Summer	0.04	0.11	0.05	0.02
Autumn	0.14*	0.12*	0.06	0.04
Winter	0.21	0.08	0.15	0.19
Nyíregyháza				
Spring	-0.01	0.03	0.10	0.04
Summer	-0.30	-0.08	0.15*	0.18*
Autumn	0.01	0.05	0.06	0.01
Winter	0.06	0.01	0.05	-0.01

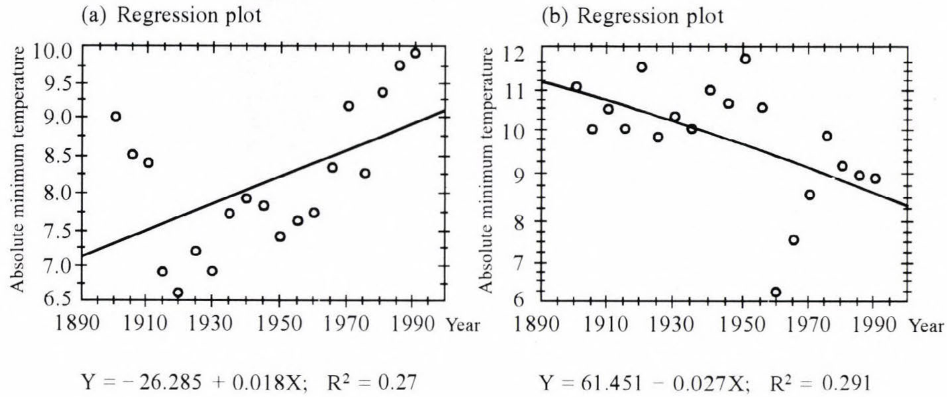


Fig. 1. Statistical characteristics of variation of absolute mimimum temperatures in summer (*a*) Nyíregyháza, (*b*) Kalocsa.

Acknowledgement—This work was supported by Hungarian Academy of Sciences as an OTKA project, under contract number is: 443. The author wishes to express her thanks to *Ms. Zsuzsa Kövér* for her assistance in computer technics.

References

Balling, J.R., Skindlov, J.A. and *Philips, D.H.*, 1990: The impact of increasing summer mean temperatures on extreme maximum and minimum temperatures in Phoenix, Arizona. *J. Climate 3,* 1491-1493.

Brázdil, R., Auer, I., Böhm, R., Budiková, M., Cegnar, T., Fasko, P., Gajic-Capka, M., Koleva, E., Lapin, M., Niedzwiedz, T., Szalai, S., Ustrnul, Z., Weber, R.O. and *Zaninovic, K.*, 1994: Trends of maximum and minimum daily temperatures in Central and Southeastern Europe - Natural variability or greenhouse signal? Submitted to *J. of Climatology.*

Ecsedy, C.J. and *Murphy, C.G.*, 1992: Global climate warming. *Water Environment 64,* 647-653.

Coops, A.J. and *Schuurmas, C.J.E.*, 1986: Detection of the CO_2 effect upon the climate over Western Europe. *Theor. Appl. Clim. 37,* 111-125.

Craddock, J.M., 1979: Methods of comparing annual record for climatic purposes. *Weather 33,* 332-346.

Gan, T.Y., 1992: Funding trends in air temperature for North-America. *Proc. of 5th International Meeting on Statistical Climatology.* June 22-26, Toronto, Ont. Canada, 19-22.

Heino, R., 1992: Changes of climatic characteristics in Fennoscandinavia. *Proc. of 5th International Meeting on Statistical Climatology.* June 22-26, Toronto, Ont. Canada, 101-104.

Karl, T.R., Kukla, G. and *Gavin, J.*, 1984: Decreasing diurnal temperature range in the United States and Canada from 1941 through 1980. *J. Clim. Appl. Meteor. 23,* 1489-1504.

Karl, T.R., Kukla, G., Razuvayev, V.N., Changery, M.J., Quayle, R.G., Heim, R.G., Easterling, Jr., D.R. and *Fu, C.B.*, 1991: Global warming: Evidence for asymmetric diurnal temperature change. *Geophys. Res. Lett. 18.* 2253-2256.

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J. and *Peterson, C.*, 1993: A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc. 74*, 1007-1023.

Pettitt, A.N., 1979: A non-parametric approach to the change point problem. *Appl. Statistics 28*, 2, 12135.

Qun, X. and *Yiwen, Y.*, 1992: Significant increasing greenhouse effect on the winter temperature of the Northern China. *Proc. of 5th International Meeting on Statistical Climatology*. June 22-26. Toronto, Ont. Canada.

Zhongwei, Y., 1992: Trends of temperature and its daily range in China. *Proc. of 5th International Meeting on Statistical Climatology*. June 22-26, Toronto, Ont. Canada, 45-48.

Zhuang, X. and *Jiliang, C.*, 1992: Changes of temperature in Beijing during the last 120 years and estimation of temperature trend in 1991. *Proc. of 5th International Meeting on Statistical Climatology*. June 22-26, Toronto, Ont. Canada, 49-52.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 2, April–June 1995

A dry matter mass growth model for maize based on meteorological and nutrient supply data

L. Lakatos

Agricultural University of Debrecen,
P.O. Box 36, H-4015 Debrecen, Hungary

(Manuscript received 30 January 1995; in final form 8 June 1995)

Abstract—A dynamic model was developed to describe the total dry matter mass above soil surface and grain dry matter mass increase for maize hybrid, Pioneer 3901 as a function of biometeorological time. It also provides estimations of the occurrence of the phenological times and of yields with accuracy of approximately 10 days and 0.8 t/ha, respectively. This corresponds to the estimation values and precision provided by other commonly used international models as CERES (*Jones* and *Kiniry*, 1986), SUCROS (*Spitters et al.*, 1989), *Dmitrenko* (1971), *Sirotenko* (1978) etc. and national models as *Ábrányi* (1979), *Dunkel et al.* (1984, 1987), *Pletser et al.* (1981) etc. As regards the number of the input parameters, the model uses 4 variables, while the nutrient supply calculation submodel, developed earlier, uses 3 variables. These variables are: data on air temperature (°C), taken at 2 meters to characterize thermal conditions; data on soil moisture deficit which is the difference between the minimum field water capacity and actual soil moisture content of a 1 m deep soil layer expressed in mm-s, to represent the hydrological conditions, global radiation in MJ/m^2 to characterize the radiation, and the nutrient supplying power of the soil, calculated by our earlier developed submodel, expressed in mg/100 g to describe the nutrient conditions. The 3 variables of the submodel are the following: temperature at 1 m deepness in °C, moisture content of a 1 m deep soil layer and precipitation, both expressed in mm. The model uses a 5 day time scale. It describes the plant dry matter mass increase with the sum of the product of response — temperature, soil moisture deficit, solar radiation, nutrient supply — and weighted functions based on probability data. As a consequence, the dual, deterministic and stochastic character of plant development is considered.

Key-words: maize, dynamic model, dry-matter, response-function, weight-function, biometeorological-time, phenological phases, grain yield.

1. Introduction

Maize used to be one of the most important food crops in Mexico, Central and South America for several centuries. According to *Weatherwax* (1954), the early civilizations of tropical America such as the Incas (in Peru, Equador, Bolivia), the Mayas (in Central America, Yucatan) and the Aztecs (in Mexico) can be considered as maize-civilizations. In Europe, maize and silage maize are produced in the areas up to latitudes 52 and 60, respectively. The size and shape of the grain vary greatly. The plant has high requirements for heat, light and water, — climatic conditions to which it was adapted in its original homeland. Had man not interfered maize it might have become extinguished by now simply because it has no mechanism for the dissemination of seeds. The high productivity can be explained by its C_4 type photosynthetic characteristics: one single seed can produce 600–1000 new ones (this number is only 50 in wheat). Researchers agree that the genetic potential of maize has far not been utilized totally yet.

This paper is dealing with maize dry matter production as a function of time and climatic factors (air temperature, soil moisture, radiation) and nutrient supply.

2. Background

According to *Szász* (1978), two main stages of the history of Agrometeorology can be distinguished:

- visual observations of climatic effects and their empirical description and classification,
- establishment of quantitative relationship among plant growth, development and productivity by statistical calculations.

The computer based modeling of plant growth and yield formation started in the nineteen seventies. Modeling at the start concerned the description of the dependence of basic physiological processes — photosynthesis, respiration — upon climatic conditions. Models were prepared to estimate yield formation as a function of photosynthetically active absorbed radiation and temperature, preconditioning that the rest of the factors — water and nutrient supply — is optimal. These models e.g. SUCROS (*Spitters et al.*, 1989), describe the potential biomass production on a particular site. Of course, water supply and transpiration have also got a significant impact on actual yield formation.

Several models had been developed by the early eighties, that described the relationship between photosynthesis and water (*Sirotenko*, 1981; *Penning de Vries*; *van Laar*, 1982). Those models that describe photosynthesis and respiration as a gas diffusion process through the stoma, consider water supply on the basis of stoma resistance and point out the importance of stoma resistance in the material and energy flow between plant and air (*Goudriaan*, 1977). Those models, on the other hand, that reduce a supposed production ratio maximum through environmental response functions, include soil water content and evaporation in considering water supply, by using a response function (or stress functions), too (*Matthaus et al.*, 1986). In recent years, a new aspect, that of modeling the effect of nutrient supply has been attracting researchers' attention. The models usually use one-day time steps, but there also exist ones operating with decade or shorter than one-day time steps.

What all the models have in common is that they all deal with a smaller or higher number of plant parameters and that they estimate yield formation on the basis of climatic and soil property characteristics. Plant development can be modeled only when the way in which the plant reacts to outside effects is known. For this, a certain knowledge of plant physiology is required. *Kenworthy* (1949), *Richards* and *Wadleigh* (1952) pointed out that plant development is inhibited even before temporary wilting point is reached. *Hagan* (1957) found that the development of plant organs and mass growth are more dependent upon soil water supply capacity than photosynthesis and respiration. He also showed in clover seed experiments that high soil water content inhibits seed production. When soil water content is low, green matter production will drop, whereas seed production will increase significantly. Temperature conditions in a particular geographical area represent decisive criteria for the natural development of a plant. All the physiological processes take place within certain ranges or tolerance intervals. As concerns temperature, it has to reach a certain minimum which is indispensable for biological activities. The activity will be at its highest when temperature is at its optimum. At maximum temperatures, however, life processes will stop working. These are the three cardinal temperature ranges. They vary widely according to the age, developmental stage and very significantly, to the species of the plant.

Simulation models, quite often represent the most basic plant functions only, such as photosynthesis, respiration and transpiration. In most of the cases, plant dry matter production as a function of time is estimated. A simulation model generally incorporates several sub-models, each of which describes a particular basic plant function. Input data:

- meteorological factors (temperature, humidity, radiation etc.),
- soil physical and chemical characteristics (soil moisture, soil temperature, water level, nitrate content etc.),
- processes that take place on the leaf surfaces (photosynthesis, respiration, transpiration etc.),
- characteristics in the stand (leaf area index, radiation distribution etc.).

Simulation models are elaborated for monitoring the plant throughout its whole life cycle and, also for estimating the yields. Since these models describe the plant development as a function of time, they are called dynamic simulation models.

3. Material

The model has to meet the requirements of both complexity and simplicity. Obviously, involving a high number of variables would provide more precise results — provided the effect of each factor is interpreted in the correct way —, a higher number of calculations, however, would result in a higher number of errors. Being aware of this and taking physiological requirements into consideration, we decided to deal with four variables (air temperature, soil moisture, global radiation and nutrient supply of the soil) these are essential for plant development.

Air temperature, and *solar radiation* data, the latter being equivalent to the global radiation measured at MJ/m^2 units as well as meteorological data necessary for submodeling the production of NO_3^--N, by natural processes, such as *soil temperature, soil moisture, precipitation* were observed at Agrometeorological Observatory of Agricultural University, Debrecen, Hungary (φ = 47°30'N, λ = 21°42'E, H = 112 m asl). The climatological data were collected in years 1964–1994.

Soil moisture data are based on lime coated chernozem soil (clay content 47%) samples taken in the observatory area, where the water table was at 8–10 m. The minimum field water capacity of the soil is 280 mm/m. In the calculations we used the moisture index (total soil moisture) expressed in millimeters for a 1 m deep sample. Let the soil moisture deficit, SMD, be equivalent to the difference between the field water capacity of a 1 m deep soil layer and the actual soil moisture content of a similar depth soil layer. The model uses this parameter instead of soil moisture value. The soil moisture data were collected in years 1964–1994, too. *Hunkár-Bacsi* (1993) found this depth satisfactory for running the CERES-model, noting, however, that in dry periods the water supplies of the deeper layers can become of importance, too.

The soil *nutrient supply* was considered equivalent to the amount of naturally produced NO_3^--N, in a 1 m deep soil layer, expressed in mg/100 g. The annual course of N-formation well characterizes the degree of the biological activities of the soil. With the Nutrient Supply Predicting Submodel, namely (NSPS) the mineralized NO_3^- amount can be estimated with 16% accuracy using the r = 0.76 correlation coefficient significant at 0.1%. The data were calculated by our earlier developed model for years 1964–1994 (*Lakatos-Szász,* 1991).

Of *plant* data, dry matter measurements were supplied by the Experiment Station of the Department of Plant Production. This place is not more than 5 km far from the Observatory and the soil samples showed identical soil types in both places. The data were collected in years 1990–1994. The phenological and grain yield data between 1975–1990 were taken at the Variety Experiment Station, which is in the neighborhood of the Observatory. All the plant data apply to 300 FAO group maize hybrid, Pioneer 3901.

4. Method

Our essential condition is quite similar to the methods applied by *Baier* (1973), *Dmitrenko* (1969, 1973), *Landsberg* and *Cutting* (1977), and *Varga-Haszonits* (1986) models. That is to say the yield formation or dry matter mass increase can be calculated by the summation of products of the environmental variables such as air temperature, soil moisture, nutrient supply and photosynthetically active radiation. In both Dmitrenko and *Rickman et al.* (1975) models describing the dry matter mass increase the variables are expressed by response functions. We suppose that the response functions are equivalent to the annual average rhythm of temperature, soil moisture, global radiation, and the nutrient supplying power of the soil. With trigonometrical series expanded by the Bessel's polinoms and extrapolation into the range of 0–1 interval, the equations of response functions — temperature, soil moisture deficit, global radiation, nutrient supplying power of the soil — can easily be determined. We also introduced such weight functions, it is quite similar to the development rate function (*Monteith*, 1981), which express the effect of a particular variable on plant development. According to *Klages* (1930, 1934), it can be supposed that the average values of the long time series, in our case it is 30 years, during the growing season are equivalent to the ecological optimum demands of the plants, which is due to the adaptation processes.

If air temperature, soil moisture deficit, solar radiation or nutrient supply data over the given period — 5 days time step — are higher or lower than the average values of long time series, the weight function values will also be lower, than the optimum values.

If the starting and ending points of the plant mass increase are known, with the summation of the products of 4 response function and the weight function minimum — according to Liebig's minimum law, the joint effect of four variables will equal the effect of the variable of the lowest value — the plant dry matter mass increase as a function of time, can be calculated.

5. Response function

In our model we used four response functions, to characterize all the principal factors of plant development i.e. the functions of thermal, hydrological, radiation, nutrient supply conditions. The response functions represent the annual climatic rhythm of the given element. According to *Klages* (1934) 'plants that are well adapted will necessarily produce a vegetational rhythm of different climatic elements in the area'.

The speed of development and biological activity of a well adapted plant, such as the maize, are influenced by the climatic, thermal, hydrological etc. conditions, which are typical of the area. Hungary's geographical situation, a little bit north of the centre of the European corn belt, shows that the maize has been well adapted here. The response functions can be produced with expansion of the average annual course of the long time series in trigonometrical series. If the maximum and minimum values of the time series are known, after the expanding in series the extrapolation into 0–1 range will produce the following response functions:

Temperature Function [*TF*(*t*)]

As it is known, temperature and day-length regulate the speed of differentiation. The differentiation of the apex, in turn, sets the speed pattern for development (*Petr et al.*, 1985).

$$TF(t) = 9.88 + 11.84 \sin\left[\frac{2\pi t}{74} + 0.26\right]. \tag{1.1}$$

Soil Moisture Deficit Function [*SMDF*(*t*)]:

$$SMDF(t) = 67.83 + 58.45 \sin\left[\frac{2\pi t}{74} + 0.68\right]. \tag{1.2}$$

Solar Radiation Function [*SRF*(*t*)]:

$$SRF(t) = 68.00 + 49.96 \sin\left[\frac{2\pi t}{74} + 0.69\right]. \tag{1.3}$$

Nutrient Supply Function [*NSF*(*t*)]:

$$NSF(t) = \left\{14.34 + 10.63 \sin\left[\frac{2\pi t}{74} + 1.1\right]\right\}\left\{1.13 + 0.61 \sin\left[\frac{2\pi t}{37} + 2.81\right]\right\}. \tag{1.4}$$

The correlation coefficient that expresses the closeness of the relationship between the measured and calculated values is r = 0.97 – 0.99. If we know the minimum and maximum values of the annual average course of the above mentioned variables we can calculate the following response functions.

Temperature Response Function [$TRF(t)$]:

$$TRF(t) = \frac{TF(t) - TF_{min}}{TF_{max} - TF_{min}}, \tag{2.1}$$

$TF(t)$: see on Eq. (1.1),
TF_{min} : minimum value of temperature function ; –1.95,
TF_{max} : maximum value of temperature function ; 21.71.

Soil Moisture Deficit Response Function [$SMDRF(t)$]:

$$SMDRF(t) = \frac{SMDF(t) - SMDF_{min}}{SMDF_{max} - SMDF_{min}}, \tag{2.2}$$

$SMDF(t)$: see on Eq. (1.2),
$SMDF_{min}$: minimum value of soil moisture deficit function ; 31.07,
$SMDF_{max}$: maximum value of soil moisture deficit function ; 126.23.

Solar Radiation Response Function [$SRRF(t)$]:

$$SRRF(t) = \frac{SRF(t) - SRF_{min}}{SRF_{max} - SRF_{min}}, \tag{2.3}$$

$SRF(t)$: see on Eq. (1.3),
SRF_{min} : minimum value of solar radiation function ; 3.62,
SRF_{max} : maximum value of solar radiation function ; 23.58.

Nutrient Supply Response Function [$NSRF(t)$]:

$$NSRF(t) = \frac{NSF(t) - NSF_{min}}{NSF_{max} - NSF_{min}}, \tag{2.4}$$

$NSF(t)$: see on Eq. (1.4),
NSF_{min} : minimum value of nutrient supply function ; 2.34,
NSF_{max} : maximum value of nutrient supply function ; 35.68.

The four response functions are represented in the *Fig. 1*. The response functions have to satisfy the assumption of normal distribution — as proved by Geary's test — and the following conditions: $0 \leq TRF(t) \leq 1$, $0 \leq SMDRF(t) \leq 1$, $0 \leq SRRF(t) \leq 1$, $0 \leq NSRF(t) \leq 1$.

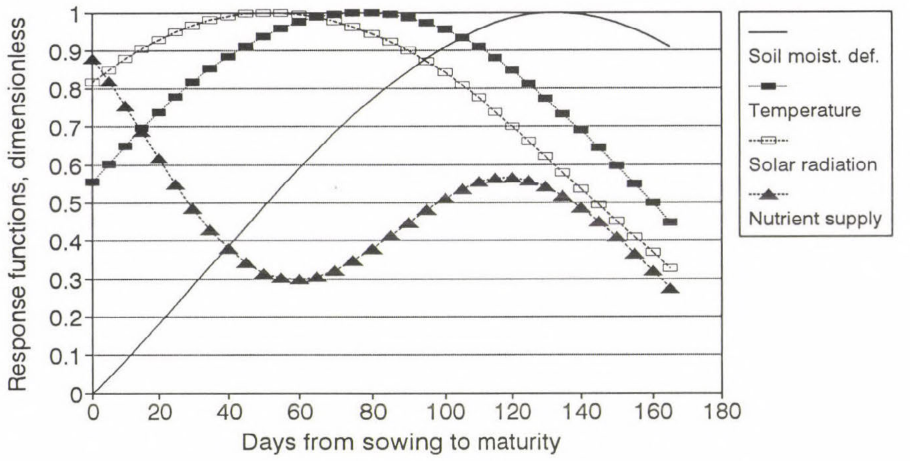


Fig. 1. Temperature, soil moisture deficit, solar radiation and nutrient supply response functions.

6. Weight functions

According to *Schimper* (1903) and *Klages* (1930, 1934) the optimum ecological requirements (thermal, hydrological, radiation, nutrient supply) of maize are more or less equal to the long term (temperature, soil moisture, solar radiation, nutrient supply of the soil) averages, during the growing season, especially in those particular geographical areas where the annual yields are high with low variability. Thus, the temperature or solar radiation, etc. optimum daily variations over the growing season correspond to the long term daily averages.

The distribution examinations — Geary's test — show that the long term 5-day temperature, soil moisture deficit, solar radiation, nutrient supply series follow a normal distribution pattern.

Let us standardize the data of the temperature and other variables series between the average sowing and maturity times for the 30 years investigated. After calculating the density function and extrapolating the ordinates of the density function of the standard normal distribution from the range of 0–0.4 into the range of 0–1, we will obtain a function which is suitable for weighting. Defining the standardized distribution functions in every 5 days and identifying the standardized values with the abscissa values of the weight function, on the ordinate the weight of the given period can be produced. For the reason of easier handling we substituted the extrapolated standard normal distribution density function as 'weighted function' with a linear curve $\eta(T)$; $\eta(SMD)$; $\eta(SR)$; $\eta(NS)$ (*Fig. 2*).

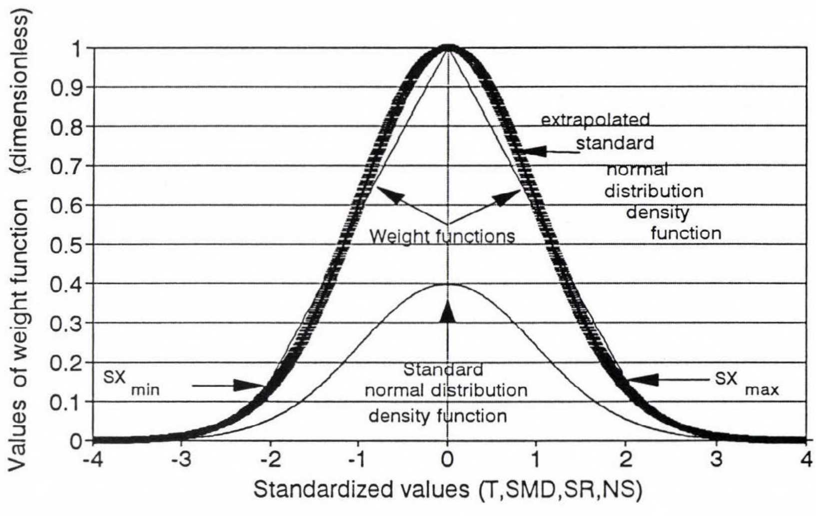


Fig. 2. Interpretation of weight functions.

As the mean value of the standardized normal distribution is 0 and the dispersion is 1, by such sample size the average produced will be equal to the mean value and in this case the weight of the period will be 1.

In the case of a satisfactory length of samples the weight of the minima and maxima would be 0, as it follows from the density function of the standard normal distribution. This, however, is not fulfilled in our case, and, so, the weights of the maxima and minima for each of the 5-day growing season periods have to be determined. As the results showed little variation over the growing season — the value of the variation coefficient (CV), never exceeded 19% maximum/minimum — we supposed that the substitution of the weight of the minimum or maximum values for the average values will not result in errors in the definition of the end value weights of the periods. The minimum values received were between 0.11–0.27 with CV-s between 8–16.

The maximum values were between 0.05–0.20 with between 6–19 CV values. Based on these values, the weight function of the variables, in 5-day time step, over the growing season can yearly be determined.

Temperature Weight Function [$\eta(T)$]:

The minimum and maximum values received were 0.11 and 0.14 with 12% and 14% CV values, respectively. Based on this knowledge, the temperature weight function, in 5-day step, between sowing and maturity, can yearly be determined with the help of the following equations.

If $T<\bar{T}$, then

$$\eta(T) = 1 - (1 - ST_{min}) \left| \frac{T - \bar{T}}{\bar{T} - T_{min}} \right|, \tag{3.1.1}$$

where

ST_{min}: the probable value of the minimum determined earlier; 0.11,
T : actual temperature of the period,
$\bar{T}$: long term average (30-year) temperature,
T_{min} : absolute minimum of the 30-year temperature series.

If $T>\bar{T}$, then

$$\eta(T) = 1 - (1 - ST_{max}) \left| \frac{T - \bar{T}}{\bar{T} - T_{max}} \right|, \tag{3.1.2}$$

where

ST_{max} : the probable value of the maximum determined earlier; 0.14,
T_{max} : absolute maximum of the 30-year temperature series.
The rest of expressions is equivalent to the previous ones.

Soil Moisture Deficit weight function [$\eta(SMD)$]:

Calculated from the standard normal distribution density function, the minimum and maximum values were 0.27 and 0.05 with 8% by 6% CV values. The distribution investigations show that, by normal distribution temperature and soil moisture deficit series, soil moisture distribution is deviated towards the lower ranges. There is higher probability of low values than of high ones, which is a consequence of the climatic conditions in the basin.

If the average soil moisture deficit over the given period is less than the long term average, i.e. $SMD < \overline{SMD}$:

$$\eta(SMD) = 1 - (1 - SSMD_{min}) \left| \frac{SMD - \overline{SMD}}{\overline{SMD} - SMD_{min}} \right|, \tag{3.2.1}$$

where

$SSMD_{min}$: the probable value of the minimum determined earlier; 0.27,
SMD : actual soil moisture deficit of the period,
$\overline{SMD}$: long term (30-year) average of the soil moisture content,
SMD_{min} : absolute minimum of the 30-year soil moisture deficit series.

If $SMD > \overline{SMD}$:

$$\eta\,(SMD) = 1 - (1 - SSMD_{max}) \left| \frac{SMD - \overline{SMD}}{SMD_{max} - SMD} \right|, \tag{3.2.2}$$

where

$SSMD_{max}$: the probable value of the maximum determined earlier; 0.05,
SMD_{max} : absolute maximum of the 30-year soil moisture deficit series.
The rest of expressions is equivalent to the previous ones.

Solar Radiation weight function [$\eta(SR)$]:

As it is generally known, the efficiency of the solar energy utilization, for the maize plant, is only 3–4% maximum. It is also known that the intensity of the photosynthesis is proportional to the number of photons mainly. Moreover, solar radiation is not a continuos process, unlike temperature and soil moisture. As mentioned the solar radiation is considered as an equivalent to the global radiation. Based on the standard normal distribution density investigations, the minimum value of the density functions was 0.13 with 13% CV value and the maximum value was 0.15 with 14% CV value. On the basis of all these, the solar radiation weight function, when the solar radiation average over the given period is below the long term average $SR < \overline{SR}$, can be written as follows:

$$\eta\,(SR) = 1 - (1 - SSR_{max}) \left| \frac{SR - \overline{SR}}{SR_{max} - \overline{SR}} \right|, \tag{3.3.1}$$

where

SSR_{min} : the probable value of the minimum determined earlier; 0.13,
SR : actual solar radiation value of the period,
$\overline{SR}$: long term (30-year) average solar radiation,
SR_{min} : absolute minimum of the 30-year solar radiation series.

In that case, if $SR > \overline{SR}$:

$$\eta\,(SR) = 1 - (1 - SSR_{min}) \left| \frac{SR - \overline{SR}}{\overline{SR} - SR_{min}} \right|, \tag{3.3.2}$$

where

SSR_{max}: the probable value of the maximum determined earlier; 0.15,
SR_{max} : absolute maximum of the 30-year solar radiation series.
The other expressions are equivalent to the earlier.

Nutrient Supply weight function [$\eta(NS)$]:

As mentioned above, the soil nutrient supply is considered equivalent to the amount of naturally produced NO_3^--N, in a 1 m deep soil layer. These values are calculated with our model developed earlier (*Lakatos-Szász*, 1991).

Based on the standard normal distribution density investigations, the minimum value of the density functions was 0.18 with 16% CV value and the maximum value was 0.20 with 19% CV value. So, the nutrient supply weight function, when the nutrient supply average over the given period is less than the long term average $NS < \overline{NS}$:

$$\eta\,(NS) = 1 - (1 - SNS_{min}) \left| \frac{NS - \overline{NS}}{\overline{NS} - NS_{min}} \right|, \tag{3.4.1}$$

where

SNS_{min} : the probable value of the minimum determined earlier; 0.18,
NS : actual nutrient supply value of the period,
$\overline{NS}$: long term (30-year) average nutrient supply,
NS_{min} : absolute minimum of the 30-year nutrient supply series.

In that case, if $NS > \overline{NS}$:

$$\eta\,(NS) = 1 - (1 - SNS_{max}) \left| \frac{NS - \overline{NS}}{NS_{max} - \overline{NS}} \right|, \tag{3.4.2}$$

where

SNS_{max} : the probable value of the maximum determined earlier; 0.20,
NS_{max} : absolute maximum of the 30-year nutrient supply series.
The other expressions are equivalent to the earlier.

Biometeorological time [$t_{biomet}(t)$]

For the description of the development of a certain plant part (grain, cob, leaf, stem) as a function of time, a reliable time scale is needed. Mass growth (total above ground or grain mass) will start at a certain stage of the plant development. For the determination of the starting point we have to introduce a biometeorological time scale. This name was introduced by *Robertson* (1968). It has to be stressed, however, that our scale is not identical with the scale used by Robertson as, besides daily temperature maxima and minima, he introduced day and night length, as well. The word 'scale' is only used to indicate that more than thermal time derived from temperature summation is meant (*Monteith*, 1981).

The character of the scale is determined by the temperature only, the daily increases, however, are in complete accordance with the plants' ecological, physiological requirements.

When constructing the scale, the external effects were taken into consideration from both meteorological and biological aspects. It was presupposed that the daily *temperature optimum* of maize plant equals the long term *temperature averages* in the particular geographical area. Thus, daily variations of the temperature optimum over the growing season correspond to the long term daily averages.

So, if the products of multiplying the values of 5 day time step temperature weight function by the corresponding values of the temperature response function are summed over the period between the sowing and maturity time, we will obtain the 'biometeorological' time.

So, the time scale is based on statistical data and alongside with its deterministic character it is also capable of treating the stochastic effects, which appear as a sum of effects taken at any point of plant development.

$$t_{biomet}(t) = \sum_{t\,=\,sowing}^{maturity} TRF(t)\ \eta\,(T(t))\,, \qquad (4)$$

where

$TRF(t)$: see on Eq. (2.1),
$\eta(T(t))$: see on Eq. (3.1.1),
t : normal time (in 5-day time steps).

Estimating the starting point of the phenological phases

A biometeorological time scale characterizes the development speed of the plant. If the scale is correctly defined, it is expected to exactly express the occurrence of the phenological phases. In our case this requirement is met as the correlation between the measured and calculated values is 0.75–0.84, and the greatest difference between the actual and estimated occurrence of the phenological phases in none of the investigated 20 years exceeds 10 days. If the biometeorological time is known, the occurrence of the phenological phases can be estimated with the following regression equations:

$$\text{Emergence } (t_{biom}) = 12.15t_{biom} + 9.24 \qquad (5.1)$$
$$\text{Tasseling } (t_{biom}) = 3.11t_{biom} + 49.36 \qquad (5.2)$$
$$\text{Silking } (t_{biom}) = 2.76t_{biom} + 56.05 \qquad (5.3)$$
$$\text{Maturity } (t_{biom}) = 4.59t_{biom} + 77.86. \qquad (5.4)$$

The least exact fitting was found with estimating tasseling time $r = 0.75$. Emergence, silking and maturity times were estimated with correlations r = 0.84, r = 0.77, and r = 0.78, respectively. This shows our model is suitable for the estimation of the occurrence of phenological phases and that it provides results with acceptable precision.

The dynamics of dry matter accumulation

According to *Vrkoc* (1977), soil and climatic conditions have a significant effect on the amount and dynamics of the biomass formation. This fact and our previous observations in the plant physiology eventually led us to conclude the biomass growth as a function of time can be described with four variables: i.e. air temperature, solar radiation, soil moisture deficit, nutrient supply. The joint effect of the four variables can be interpreted by additive or multiplicative relations. The multiplicative approach is supported by the fact that each of the variables is essential for survival which means that minimum availability of any of the four factors will result in a significant decrease in their joint effect. In the additive case it is not realized in the same extent. Knowing the response functions and probability weights of each variable — and using the Liebig's minimum law — effect is the summation of the products of the four response functions multiplied by the lowest value of the weight function, the dry matter production of maize can be described. Accordingly, the model equation is this:

$$DM(t_{biom}) = \sum_{t_{biom}=0}^{m} \{MRF(t_{biom})\}\{WF(t_{biom})\}, \qquad (6)$$

$DM(t_{\text{biom}})$: plant mass increase as a function of biometeorological time,
$MRF(t_{\text{biom}}) = TRF(t_{\text{biom}})\ SRRF(t_{\text{biom}})\ SMDRF(t_{\text{biom}})\ NSRF(t_{\text{biom}})$,
$WF(t_{\text{biom}}) = \min\ [\eta(T(t_{\text{biom}})),\ \eta(SR(t_{\text{biom}})),\ \eta(SMD(t_{\text{biom}})),\ \eta(NS(t_{\text{biom}}))]$.

With the help of the equation above, the daily (5 day) plant mass growth can be determined. The relationship between the dimensionless cumulative results of our model the dry matter content expressed in g/plant dimension can be characterized by the following equations:

$$DM_{meas}(dm_{calc}) = 44.13\ dm_{calc} - 23.09, \qquad (7.1)$$

for total biomass above the soil surface (*Fig. 3*) and

$$DM_{meas}(dm_{calc}) = 78.10\ dm_{calc} - 77.85 \qquad (7.2)$$

for grain mass on the cob (*Fig. 4*). In these equations *DM* is the measured and *dm* is the calculated dry matter content.

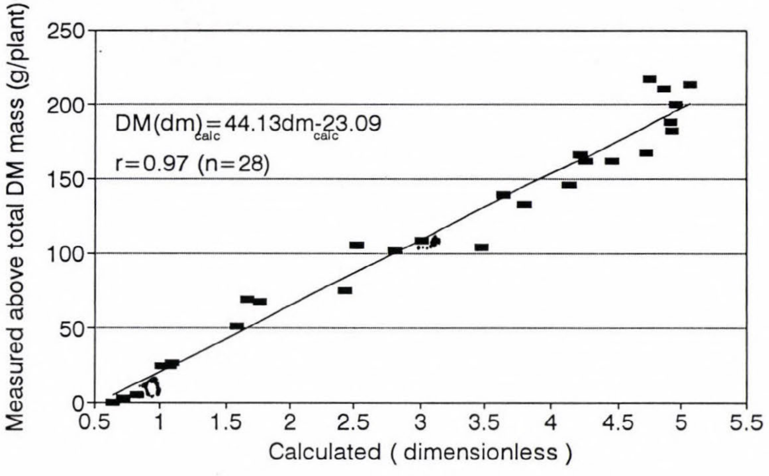


Fig. 3. Relationship between measured total biomass above soil surface and estimated dry matter mass.

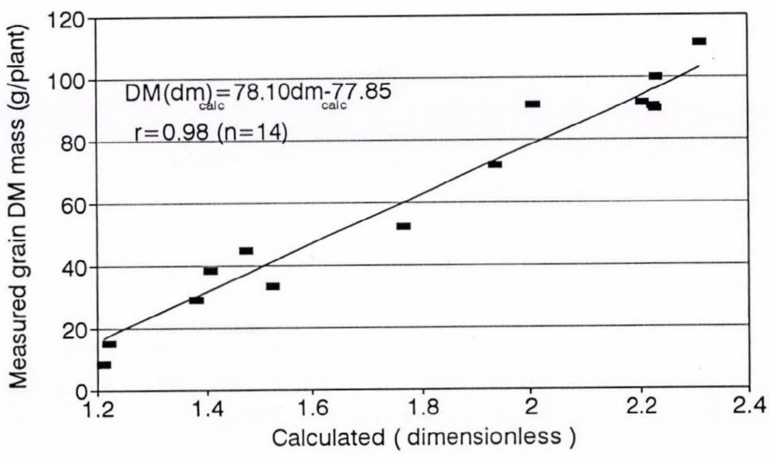


Fig. 4. Relationship between measured grain mass and estimated dry matter mass.

There is a significant relation between the measured and the calculated values, in above soil biomass total and grain mass accumulation dynamics, r = 0.97 and r = 0.98 at p = 0.1%. The testing of a model is usually done on outside control material. In our case it was the dry matter mass growth prediction for year 1994. If the *starting point* of grain formation which can be read on the biometeorological time scale (on the basis of 3 investigated years it was 12.5, with very slight differences) and the *final point*, i.e. the maturity date (it was 22.0, also with a very slight differences) are known, the grain dry matter mass increase can be calculated, with the model being run between these two points.

As, it can be seen in *Fig. 5*, both the total biomass above the soil surface and grain mass growth as a function of time can be predicted with the precision of 8%.

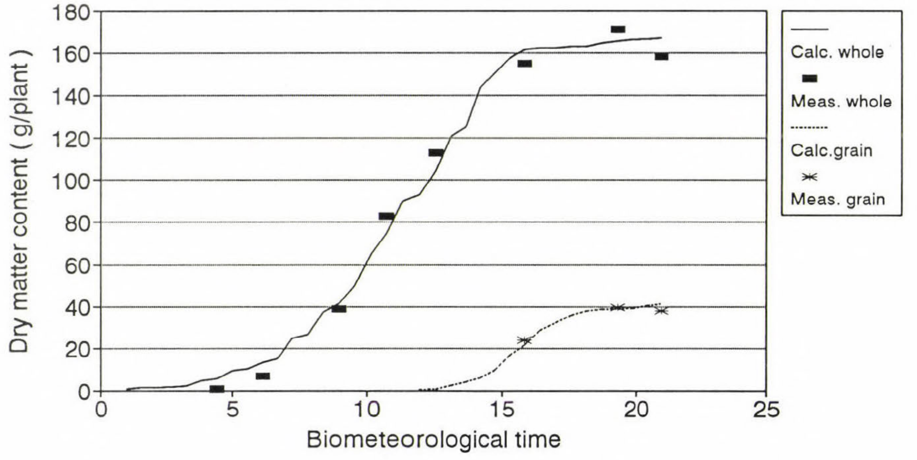


Fig. 5. The mesured and estimated dry matter mass growth of the total biomass above soil surface and the grain yield in 1994.

Prediction of the grain yield quality

The mass growth data of the total plant and grain dry matter data are essential for making yield estimations. The relation between dry matter accumulation and the yield quantity was examined by *Hunkár* (1990). She found that there is a significant relation between the yield quantity and the maximum dry matter content values.

The data of the available 4 test years — period between 1991–1994 — show a significant, at $p = 0.1\%$, relation between the measured maximum dry matter content value and the grain yield amount, the correlation coefficient is $r = 0.96$. The regression equation is:

$$Y(\max DM_{grain}) = 0.08 \max DM_{grain} - 0.12\,, \tag{8}$$

where Y is the quantity of grain yield in (t/ha), and $max\ DM_{grain}$ is the maximum grain dry matter content value in (g/plant). This equation can be generalized only if the stem numbers/ha rate is the same in every investigated year (it was about 70 thousand stems/ha in our case). Let us suppose that this assumption is realized in every investigated year.

The outside control material, which is necessary for testing, in the current case, data series between 1975–1990 obtained at the Variety Research Station. If we run the model from the starting point of grain formation determined earlier — it is 12.5 — to the maturity date, i.e. 22 biometeorological time points, the grain dry matter content maximum value can be determined. In the investigated period of 1975–1990, the values received show a significant relation with grain yield quantity ($r = 0.90$) at $p = 1\%$. The average error of measured and calculated values was below 0.8 t/ha (*Fig. 6*).

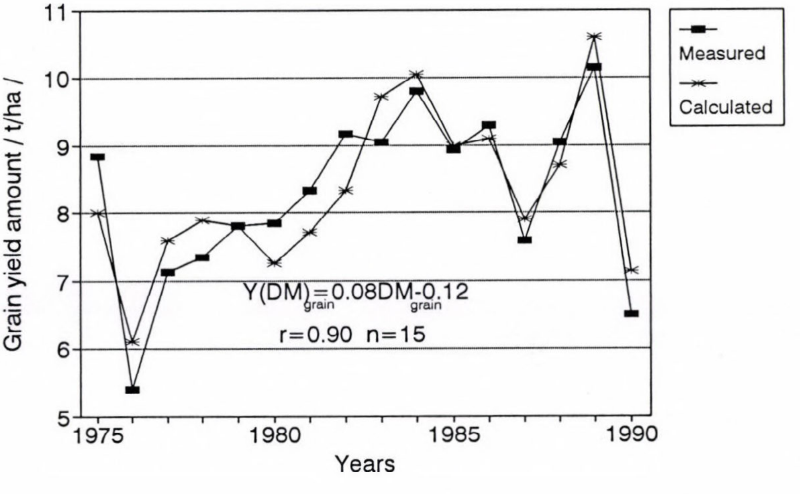


Fig. 6. The measured and estimated grain yield amount (t/ha) during the period of 1975-1990.

7. Conclusions

The results apply to a medium-duration maize hybrid, Pioneer 3901. This hybrid and 300 FAO-groups are the major cultivated hybrids in eastern and other regions of the country. The annual yield average of a large cultural area involves the yields of several different varieties. There are large differences in their productivity, drought and disease resistance. Varieties with new traits can change significantly in their weather tolerance, their tolerance to certain climatic effects may increase, to others it may decrease. Long duration cultivation of a variety may cause changes in certain characteristics.

So, we cannot expect that a plant-weather model developed for a variety with certain genetic potentials to work perfectly for varieties with genetic potentials other than those. The model presented here did not take the dry matter decrease of maize during its growing period into consideration.

We supposed that the mass growth of dry matter was a monotonously increasing process. We think that, this supposition could be realized, if the principal supplies (thermal, hydrological, radiation, nutrient) were nearby optimum. The model uses a low number of input parameters which makes it easier to deal with. Moreover, the development of a variety function for maturity groups would widen the range of model utilization.

References

Ábrányi, A., 1979: Meteorological modeling of growth and development of maize (Zea mays L.) (in Hungarian). *Beszámolók 1976*. Orsz. Meteorológiai Szolg., Budapest, 151-156.

Baier, W., 1973: Crop-weather analysis model: review and model development. *J. Applied Meteorology*, 937-947.

Dmitrenko, V.P., 1969: Study about the effect of optimum values of precipitation and air temperature on crops yields (in Russian). *Trudü UNIGI*, No. 84, 26-46.

Dmitrenko, V.P., 1971: Yield predicting model on the basis of hydrological parameters (in Russian). *Meteorologia i Gidrologia*, No. 5, 84-91.

Dmitrenko, V.P., 1973: Determine the effect of precipitation on the yield formation of arable crops (in Russian). *Trudü UNIGI*, No. 128, 3-22.

Dunkel, Z., 1984: Dynamical (simulation) modelling of growth (increase of mass) of plough-land plants (in Hungarian). *Beszámolók* 1981. Országos Meteorológiai Szolgálat, Budapest, 269-284.

Dunkel, Z., *Hunkár, M.* and *Zárbok, Zs.*, 1987: Description of the development of maize (Zea mays L.) using dynamic - simulation plant growth model (in Hungarian). *Időjárás 91*, 197-208.

Goudriaan, J., 1977: *Crop Micrometeorology a Simulation Study*. Simulation Monographs. PUDOC, Wageningen.

Hagan, R.M., 1957: Water-soil-plant relations. *Claif. Agr. 11*, 9-12.

Hunkár, M., 1990: The impact of weather on dry matter production of maize (in Hungarian). *Beszámolók* 1986. Országos Meteorológiai Szolgálat, Budapest, 92-99.

Hunkár, M. and *Bacsi, Zs.*, 1993: Attempts by soil-plant weather models. In *Meteorology and Agronomy*. Országos Meteorológiai Szolgálat, Budapest, 59-65.

Jones, S.A. and *Kiniry, J.R.*, 1986: *CERES-Maize: a Simulation Model of Maize Growth and Development*. Texas A&M University Press, Texas.

Kenworthy, A.L., 1949: Soil moisture and growth of apple trees. *Amer. Soc. Hort. Sci. Proc. 54*, 29-39.

Klages, K.H.W., 1930: Geographical distribution of variability in the yields of field crops in the states of the Mississippi Valley. *Ecol. 11*, 293-306.

Klages, K.H.W., 1934: Geographical distribution of variability in the yields of cereal crops in South Dakota. *Ecol. 12*, 334-345.

Lakatos, L. and *Szász, G.*, 1991: Climatic effects on the changes of the N-supplying power of soils. *Időjárás 95*, 289-301.

Lansberg, J.J. and *Cutting, C.V.*, 1977: *Environmental Effects on Crop Physiology*. Academic Press, London.

Matthaus, E., *Mirschel, W.*, *Kretschmer, H.*, *Künkel, K.* and *Klank, I.* 1986: The winter wheat crop model TRITSIM of the Agroecosystem AGROSIM-W. *Computer Aided Modelling and Simulation of the Winter Wheat Agroecosystem for Integrated*

Pest. Management Academie der Landwirtschwissenschaften der DDR, 43-77.

Monteith, J.L. 1981: Climatic variation and the growth of crops. *Quart. J. Roy. Meteor. Soc. 107*, 749-774.

Penning de Vries, F.W.T. and *van Laar, H.H.*, 1982: *Simulation of Plant Growth and Crop Production.* Wageningen: Pudoc-111 (Simulation Monograph).

Petr, J. et al., 1985: *Yield Formation of Main Arable Crops* (in Hungarian). Mezőgazdasági Kiadó, Budapest.

Pletser et al., 1981: Relationship between the generative developmental stages of maize (Zea mays L.) (in Hungarian). *Beszámolók 1976.* Országos Meteorológiai Szolgálat, Budapest, 219-225.

Richards, L.A. and *Wadleigh, C.H.*, 1952: *Soil Water and Plant Growth.* Soil Physical Conditions and Plant Growth. Academic, New York.

Rickman, R.W., Raming, R.E. and *Allmaras, R.R.*, 1975: Modeling dry matter accumulation in dryland winter wheat. *Agronomy Journal 67*, 283-289.

Robertson, G.W., 1968: A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. *Int. J. Biometeorology 12*, 191-223.

Schimper, A.F.W., 1903: *Plant Geography on a Physiological Basis.* Clarendon, Oxford.

Sirotenko, O.D., 1978: Physico-matematical modeling in agrometeorology (in Russian). *Meteorologia i Gidrologia 3*, 80-88.

Sirotenko, O.D., 1981: *Mathematical Modelling of Moisture and Heat Regime and Productivity of Agricultural Ecosystem* (in Russian). Gidrometeoizdat, Leningrad.

Spitters, C.J.T., van Keulen, H. and *van Kraalingen, D.W.G.*, 1989: A simple and universal crop growth simulator SUCROS 87. In *Simulation and Systems Management Crop Protection* (eds.: *R. Rabbinge, S.A. Ward* and *H.H. van Laar*). Simulation Monographs, PUDOC, Wageningen, 147-181.

Szász G., 1978: Eine Studie über die dreistufige Entwicklung der agrarmeteorologischen Wissenschaft (Wissenschaftgeschichtliches Essay). *Foliae Agrarmeteorol. 1*, 1-41.

Varga-Haszonits, Z., 1986: Methodical principles of multiplicative crop-weather model building. *Beszámolók 1983.* Országos Meteorológiai Szolg., Budapest, 155-164.

Vrkoc, F., 1977: Yield formation of cereales. In *Yield Formation of Main Arable Crops* (in Hungarian). Mezőgazdasági Kiadó, Budapest, 115-116.

Weatherwax, P., 1954: *Indian Corn is Old America.* Macmillan, New York.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 2, April–June 1995

Influence of the hilly relief on the water balance of vineyard

St. Stoychev

Bulgarian Academy of Sciences, Institute of Meteorology and Hydrology, Tzarigradsko Chaussee 66, Sofia 1184, Bulgaria

(Manuscript received 3 October 1993; in final form 1 August 1994)

Abstract—Under various hilly relief, according to the locality of the plots the moistening conditions change essentially. The different moistening forms various conditions of water consumption and moisture supply of the vineyard. An uninterrupted three-year microclimatic experiment upon vine plantations, grown without irrigation in the various localities of the hilly relief in the region of the town of Perushtitsa, Plovdiv district, has been carried out for determining the influence of the hilly relief microclimate upon above mentioned agricultural-climatic indices in South Bulgaria.

The estimation of the hilly relief influence on the water regime, the water consumption and the moisture supply of vineyard have been obtained after a detailed analysis of a complex of meteorological, agrometeorological and biological factors in different relief. It has been established that the vine-stocks grown without irrigation, are supplied with moisture in the beginning of the vegetation and through the interphase periods from the budding to the end of blooming. During the interphase periods from the end of blooming to the defoliation the moisture content has been mainly below the optimal ones. The moisture content has been the highest in the beginning of the vegetation, after that it has continuously decreased and in the beginning of the autumn it has become the lowest. The moisture accumulation has started with the transition of vineyard from vegetation to quiet and with increasing of the precipitation amount. The total water consumption of vine-stock, grown without irrigation, has been in direct connection with the amount of precipitation, fallen during the vegetation period. It has shown that in various conditions of hilly relief the differences in the microclimate, the soils and the vineyard water consumption have led to considerable changes in grape yield.

Key-word: water balance, water consumption, water supply of vineyard, soil moisture.

1. Introduction

The unsteady moisture supply of vineyard, grown without irrigation in plots situated on the slopes of various inclinations and exposures in the hilly relief, has been consequence of different water quantities resulting from the precipitation and its redistribution there. The differences in the conditions of moistening have created such differences in the water consumption and the moisture supply of vineyard too. It follows to expect high yields with excellent quality of grapes there, where the microclimatic and soil conditions have been the most favourable and the moisture conditions — nearest to the optimal ones. The knowledge of the microclimatic features in the distribution of these agroclimatic indices is important for the agricultural practice.

2. Research material and methods

The present investigation has been a part of a large microclimatic experiment, carried out continuously for three years (Jan 1978–Dec 1980) in the vine-stock plantations of the Scientific and Industrial Complex 'G.Dimitrov' in the region of the town of Perushtitsa, district of Plovdiv. The territory under study is situated in the central part of South Bulgaria, in the region near the north slopes of the Rhodope mountain. It spreads over 20 km^2, and is found at 199 to 400 m above sea-level and as a matter of fact is a valley with a slight inclination to the N (up to 1°) bordered from the S by the North-Rhodopean slopes, which in the given region are over 1000 m above sea level, from the E, W and to a great degree from the N by hillranges with a relative height up to 100 m, which are off-branches of the North-Rhodopean slope. The valley is ellipsis-shaped with 4 and 2 km axes.

The continuous microclimatic observations have been implemented in two profiles, situated in massifs of vine-stock plantations mainly of the variety Bolgar. The plots with variety Bolgar are located in the middle and lower parts of the slopes and throughout the valley. The peaks and the upper parts of the slopes are pastures with well developed herbage. The vine-bushes are planted at 3.40 × 1.20 m distance in 'high-stem Guillot' forming. The grape-vine is grown without irrigation and is not covered up for the winter. The characteristics of the microclimatic points along the profiles, where the soil moisture has been determined as well as of the reference meteorological station for the experiment which is found at the basic profile, taken from the topographical map, are presented in *Table 1*.

In the profiles which have been investigated on the slopes with 3–7° steepness there are medium eroded brown forest soils (points 2 and 5), high-carbonated, heavy clayey, and among them some islands of humous carbonated, slight clayey and stony ones (point 3). The valley is covered by alluvial soils, slightly clayey ones (point 6). In the upper sections of the slopes and on the tops of the elevations the soils are humous-carbonated, fine, highly eroded and stony.

In these profiles the humous horizon reaches 20 cm with alluvial soils and 40–50 cm with the rest. The whole profile of the humous carbonated soil is about 40–60 cm thick, of the brown forest soil about 100 cm and of the alluvial soil over 200 cm. The humous and carbonates content is low with the alluvial soil (up to 1% and 4.3%, respectively) and is the highest with the humous-carbonated soil (2.0–2.2% and 23.8–27.6%). The brown forest soils content 1.4–1.8% humous in the ploughed layer and a low quantity of carbonates. The soil pH varies between 6.0 and 7.2, i.e. is neutral and has got low alcalinity.

Table 1. Characteristics of the microclimatic points in which soil moisture has been determined and of the base meteorological station at Perushtitsa

No. of point	Location	Exposure	Distance between points (m)	Altitude asl (m)	Elevation (m)	Steepness of the slope (degree)	Vegetation
2	A	NW	675	314	115	5	Bolgar
3	B	NW	835	268	69	3	Bolgar
0	C	NW	2675	244	45	1	Vineyard at a distance of 100 m
6	D	NW	925	199	0	<1	Bolgar
5	E	NE		220	21	7	Italian Riesling

Legend: A – middle part of the slope; B – lower part of the slope; C – meteorological station; D – valley; E – lower part of the slope

Agrohydrological constants of the soil vary mainly because of differences in the mechanical composition. Humidity of the steady withering varies from 7.3% with alluvial soil to 18.2% with brown forest soil. The limited field capacity reaches 17.8% in the case of alluvial soil and 30.4% at some horizons of the brown forest soils (*Stoychev* and *Dimov*, 1986).

The weather during the investigation period was marked by a heightened background of the air humidity, higher recurrence of changeable-cloudy weather, lower values of the radiation characteristics and suppressed temperature regime in comparison to the many years' average. The amount of precipitation in general during these years was near the normal value, but its distribution within the period was extremely uneven.

Microclimatic observations were made continuously in 6 points from meteorological instrument shelters including maximum, minimum and time dependently the air temperature every day according to a schedule. At all points the 24-hour changes in temperature were registered uninterruptedly by thermographs. The shelters were placed at the height of 150 cm. At the same points precipitation was measured with Wild's raingauge. All the visual meteorological and agrometeorological observations were made, too. The shelters and the gauges placed at the points in the vineyards were put just between the rows. Raingauges were placed where there were no vine-stocks. The standard station of the meteorological network at Perushtitsa, which has been operated with some interruptions between 1934 and 1981, was the basic station for the experiment. The meteorological observations took place regularly 3 times a day in the standard for Bulgaria time-step (at 7, 14 and 21 h according to Sun Mean Time) following the Manual (*Dabov*, 1971).

In the region of 2, 3, 6 and 5 (see Table 1) systematically and according to the method generally accepted (*A Guide for Agrometeorological Observations*, 1960) the soil moisture was determined by soil sampling with a fourfold recurrency on every 7th, 17th and 27th day of the month. Samples got evaluated immediately at the soil laboratory nearby.

At the points situated in vineyards there were daily phenological observations throughout the vegetation period as well as some others aimed at the state of the culture and at the proceeding of the agricultural work in accordance with the method accepted at the National Institute of Meteorology and Hydrology of Bulgaria (*A Guide for Agrometeorological Observations*, 1960).

All microclimatological observations in the grape-vine culture were made at ordinary production plots of the Scientific and Industrial Complex. The Perushtitsa region is known as one of the basic producer regions of the country for table wine, mainly of the basic variety for export — Bolgar.

The water balance of vineyard under natural circumstances of moistening was investigated on the basis of the materials on the dynamics of productive moisture contents at different sites of the hilly relief and with different types of soil within the experimental period.

The water consumption i.e. the effective evapotranspiration during the vegetation period has been determined with the method of water balance:

$$E = W_1 - W_2 + z - f,$$

where E is the water consumption for a given period in mm, W_1 is soil moisture content at the beginning of the period in mm, W_2 is soil moisture content at the end of the period in mm, z is precipitation amount for the period in mm and f is surface run off from the precipitation assessed by the method of run off coefficients in mm (*Onchev*, 1974).

The vineyard's moisture supply has been assessed by making a comparison between the productive soil moisture content and the lower border of the optimum moistening (70–75% of the limited field moisture capacity).

The biological observations upon the vine-stocks have been carried out through common accepted methods with participation of a collective from Department of Viticulture of the High Agricultural Institute in Plovdiv.

3. Results and discussion

The investigation period has been characterized with considerable amounts of precipitation and comparatively high soil moisture content both on the slopes and in the valley. For the water balance regime of vineyard at sufficient moistening the upper 1 m soil layer, which can name active (*Magrisso*, 1970), is of determinative importance. Therefore, the analysis of the water balance regime has been effectuated for the 0–50 and 0–100 cm soil layers in which the basic part of the vine-stock root system has been disposed.

The optimum moisture content of the root zone for the vine-stock is equal to 70–75% of the limited field moisture capacity (LFMC) and more (*Winkler*, 1962; *Turmanidze*, 1981; *Fursa*, 1986). At such a degree of the moistening of the soil during almost the whole vegetation period (from the beginning of vegetation till the beginning of ripening of the grapes) the vineculture has an optimal growing and developing and gives high yields. The soil moisture content in spring is determined basically by the precipitation fallen in the cold period of the year (November–March). In the region under study in the given period (November–March) for the time of investigation in the microclimatic points the precipitation amounted to 175–186 mm (82–87% of the many years'norm at the meteorological station, which has been 214 mm). As we can see in *Fig. 1*, where the average annual course of the soil moisture content is presented, during the cold period of the year when the natural moisture content in the soil occurs, the productive moisture content are high and near to LFMC all over.

Since during the cold period the vine culture does not vegetate, the water losses from the soil are not too much and occur on account of evaporation and run off only. During the warm period the moisture leaving the soil is determined mainly by transpiration and in a smaller degree by evaporation from the soil surface. The water consumption of grape-vine plants during the vegetation period is uneven and changes according to the phases of development. That is why it is more convenient to analyse the soil moisture content, the water consumption and the soil moisture supply of vine-stocks according to the interphase periods of the vine culture's evolution. Investigation has been performed for the following interphase periods: budding–beginning of blooming; beginning of blooming–end of blooming; end of blooming–beginning of ripening of grapes; begining of ripening of grapes–physiological ripeness; physiological ripeness–defoliation. The dates of the beginning, the end and duration of these interphase periods during the years of investigation at the microclimatologic points situated in vineyards are presented in *Table 2*. As it can be seen from Table 2 and Fig. 1 at the time of blooming in spring the productive moisture content, i.e. available water in the 0–50 and 0–100 cm layers were high and near to LFMC. They varied between 44 and 90 mm in the 0–50 cm layer and between 148 and 180 mm in the 0–100 cm layer depending on the type of soil and the weather during the period.

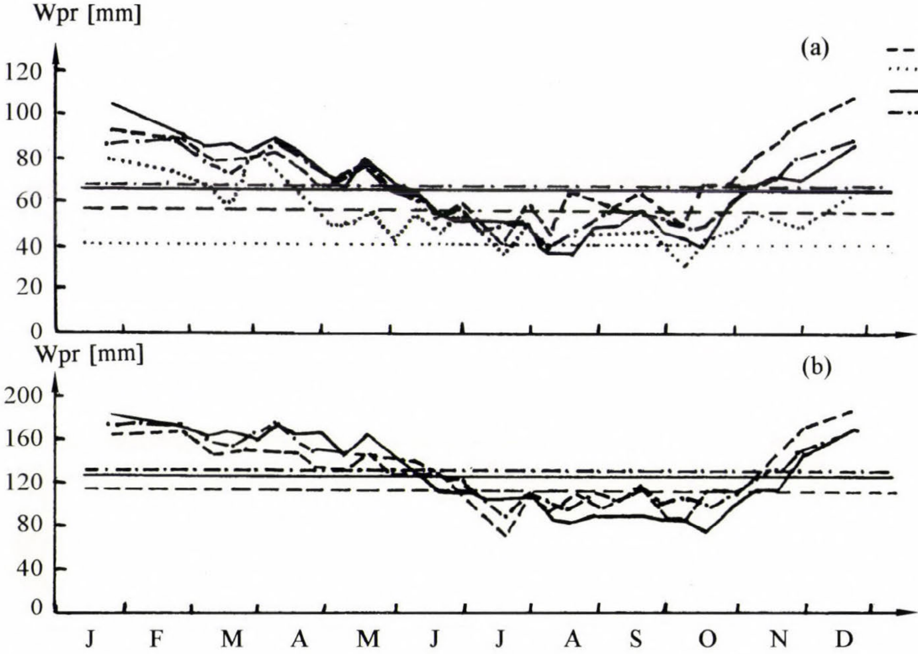


Fig. 1. Annual course of productive moisture (Wpr) in the investigation period (1978-1980). (*a*) 0–50 cm soil layer, (*b*) 0–100 cm soil layer; 2, 3, 6 and 5 — microclimatic points.

During the 'budding–beginning of blooming' interphase period, the duration of which depending on the plot's location comes up to 55–62 days in average (Table 2), the mean water consumption from the soil is negligible and its value was 6–21 mm in the 0–50 cm soil layer and 26–38 mm in the 0–100 cm layer. The average amount of precipitation is 141 mm, while the normal value being 153 mm (*Table 3*). In the course of this interphase period in the years of investigation the available soil moisture was all over big (Fig. 1). The air temperature was moderate. The foliage surface not everywhere developed. Under such circumstances the average summary of the water consumption of the vineyard varied from 168 mm in the 0–50 cm soil layer to 182 mm in the 0–100 cm layer (Table 3).

The analysis of the moisture content has revealed that on the plots of investigation the stocks of productive moisture for this interphase period stayed at the optimum level i.e. they were near and over 75% from LFMC; hence the vine-stocks were well supplied with moisture during the interphase period lasting from the budding till the beginning of blooming. This time all parts of vine-plant are in intensive growing, first of all its sprouts and leaves and from the latter the lower ones in particular, which at the end of the period reach their normal size.

The 'beginning of blooming–end of blooming' interphase period which is of short duration — 6 to 8 days in general — occurs in June (Table 2). It is essential as regards to the outcome of the yields both for the current and the next year. At this time the fecundation of the blossoms is going on and the next year yield's buds are being lain. Beside the necessary air temperature for the grape-vine's getting through this interphase period normally also optimum soil moisture content is needed.

Table 2. Mean dates of the beginning, end and duration of the interphase periods (days) at the microclimatic points in the investigation period (1978-1980)

Plot points	Budding – beginning of blooming			Beginning of blooming – end of blooming			End of blooming – beginning of ripening of grapes		
	A	B	C	A	B	C	A	B	C
2	09.04	10.06	62	10.06	16.06	6	16.06	12.08	57
3	08.04	08.06	61	08.06	16.06	8	16.06	10.08	55
6	12.04	08.06	57	08.06	16.06	8	16.06	09.08	54
5	10.04	04.06	55	04.06	11.06	7	11.06	12.08	62

Continued Table 2

Beginning of ripening of grapes – physiological ripeness			Physiological ripeness – defoliation		
A	B	C	A	B	C
12.08	22.09	41	22.09	03.11	43
10.08	16.09	37	16.09	04.11	49
09.08	11.09	33	11.09	02.11	52
12.08	21.09	40	21.09	03.11	43

Legend: A – beginning, B – end, C – duration

The mean productive moisture content was 47–60 mm (0–50 cm) and 118–130 mm (0–100 cm), respectively (Fig. 1). The moisture content in this interphase period with rare exceptions (point 6 in 1979) has been at the optimum. The vineyard's total water consumption from the 1 meter soil layer during this interphase period was 2–15 mm of water in average. In some years the fluctuations in the water consumption values depending on the locations of the plots and the soil type reached up to 25 mm. Generally speaking, during this period the mean moisture loss is low (Table 3) and in the case of precipitation of 3 mm even moisture accumulation could be observed (point 2).

Table 3. Mean water consumption of vineyards (mm) in two different soil layers by interphase periods in the region of Perushtitsa (1978–1980)

Plot points	0 - 50 cm			0 - 100 cm		
	From the soil	Precipi-tation	Amount	From the soil	Precipi-tation	Amount
			Budding — beginning of blooming			
2	6	162	168	26	162	188
3	15	152	167	–	–	–
6	16	144	160	28	144	172
5	21	157	178	38	157	195
			Beginning of blooming — end of blooming			
2	2	3	5	-1	3	2
3	3	2	5	–	–	–
6	7	2	9	8	2	10
5	15	2	17	2	2	4
			End of blooming — beginning of ripening of the grapes			
2	5	92	97	16	92	108
3	2	75	77	–	–	–
6	19	71	90	41	71	112
5	19	73	92	45	73	118
			Beginning of ripening of the grapes — physiological ripeness			
2	-7	76	69	-6	70	64
3	-4	80	76	–	–	–
6	-21	86	65	1	61	62
5	-13	100	87	-18	72	54
			Physiological ripeness — defoliation			
2	-13	70	57	-6	70	64
3	-4	70	66	–	–	–
6	-6	61	55	1	61	62
5	-12	72	60	-18	72	54
			Total amount for the budding — defoliation period			
2	6	333	339	30	333	363
3	16	309	325	–	–	–
6	21	303	324	55	303	358
5	42	332	374	64	332	396

In the course of this interphase period the moisture content continuously decreased, remaining at the optimum level throughout the 1 m soil layer. So the conditions of the moistening of vineyard's root zone stayed at the optimum level in the mentioned interphase period during the years of investigation.

The 'end of blooming–beginning of ripening of grapes' interphase period is long: 54–62 days (Table 2). This is a period of intensive growing of the grapes and maximum development of the vegetative mass of the vine-plant. During this period the mean moisture content in the 0–50 cm soil layer amounted to 44–51 mm and in the 0–100 cm one to 96–105 mm. The available water content here was characterized by constant decrease as the time passed; it was the most explicit in the valley. It has to be taken into consideration that to a large extent of the period passed with soil moisture content below optimum, particularly in the valley, but in consequence of the well developed root system the vine stocks in the valley have used water from the 100–200 cm soil layer (Fig. 1).

The mean summary of the water consumption from the 1 m soil layer amounted to 108–118 mm of water, from which 16–45 mm were utilized from the soil and 71–92 mm were from precipitation.

During the 'beginning of ripening of grapes–physiological ripeness' interphase period the necessity of the plants in water decreases considerably in consequence of the reduced activity of the lower and middle range of foliage, the standstill in the growing of the sprouts and their intensive lignification. The available water content in the soil during the period was mainly below optimum with the exception of the humous-carbonated soil (point 3) and amounted to 92–108 mm in the 1 m soil layer. The mean amount of precipitation during this period was considerable: 117 mm with many years' average being 101 mm.

The total water consumption of the vineyard was lower than during the previous interphase period (Table 3). The moisture supply of the grape-vine for the period was mostly satisfactory (Fig. 1).

In the 'physiological ripeness–defoliation' interphase period the grape-vine's water demand becomes still lower. This is the period when the vine-stock makes a transition from vegetation towards a quiet. The mean available water grew gradually and at the end of the period amounted to 43–78 mm (0–50 cm) and 90–126 mm (0–100 cm) i.e. over or near the optimum level (70–75% of LFMC). The mean amount of the precipitation was 93 mm i.e. below many years' average, which was 104 mm. During this period the accumulation of soil moisture content occurs (Fig. 1).

The total water consumption of the vineyard at this time is considerably less compared to the previous period (Table 3). During the whole interphase period the vine stocks are well supplied with moisture (Fig. 1).

The vineyard mean total water consumption for the vegetation period from budding till the physiological ripeness of grapes, which is of economic significance, made up to 325–374 mm in the 0–50 cm soil layer and to 358–396 mm in the 0–100 cm layer, when the mean precipitation amount was 303 to 333 mm for the same period (Table 3). The moistening circumstances of the investigated region make possible the receiving of fairly good yields of table grapes of superior quality.

The effective evapotranspiration value depends on the soil moisture content and on the biological properties of the vineculture (*Fursa*, 1986). Based on our experimental data the biological curves of the vineyard water consumption for the period of investigation have been drawn (*Fig. 2*). Taking into consideration the biological peculiarities of grape-stock we have drawn biological curves for the basic periods of development we have studied already. The total water consumption was brought to the average for a given interphase period since in this case one can see most clearly the differences in the factual water consumption by individual phases, which are conditioned by the seasonal course of evaporation. The 'beginning of blooming–end of blooming' interphase period was not studied separately because of its shortness (6–8 days).

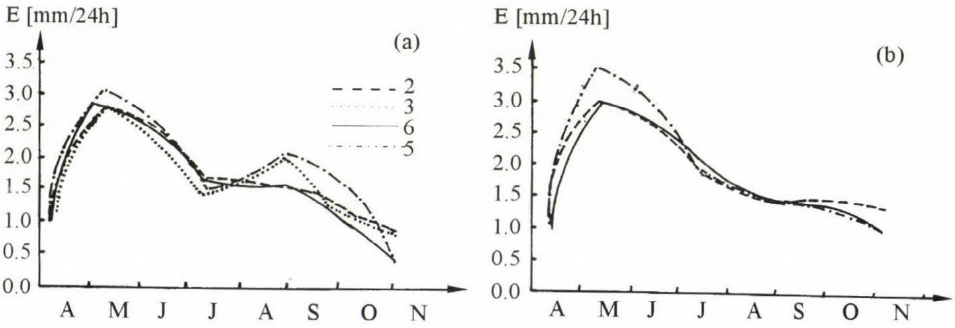


Fig. 2. Biological curves of the water consumption of vineyard for the region of Perushtitsa (1978–1980). (*a*) 0–50 cm soil layer, (*b*) 0–100 cm soil layer; 2, 3, 6 and 5 — microclimatic points.

Although the phenological observations have been effectuated on different grape-vine varieties Bolgar and Italian Riesling, their water consumption was allied, as at the latter variety it was little bigger.

In Fig. 2 it can be seen that the biological water consumption of the vineyard differs during the different interphase periods and also that the water consumption from the 0–50 cm soil layer varies to a significantly greater degree. The curves of water consumption for the 0–100 cm soil layer are smoother although the water consumption from the 50–100 cm soil layer goes up significantly in the 3rd interphase period 'end of blooming–beginning of ripening of grapes' when the amount of available water in the halfmeter surface soil layer decreases considerably.

Minimum water consumption is characteristic of the phases at the beginning and the end of development, but it is the highest during the period of active vegetation with maximum increase of the biomass of the bush. According to Fig. 2 the 24-hour maximum of water comsumption occurs through the vegetation from the beginning of blooming till the beginning of ripening (growing) of the grapes and amounts to 2.7–3.2 mm in the 0–50 cm soil layer and to 3.0–3.5 mm in the 0–100 cm soil layer. From the analysis of the correlation of the vineyard actual water consumption in the halfmeter and onemeter soil layers follows, that if the halfmeter soil layer is well supplied with moisture then the water consumption of the vineyard comes basically from this layer. According to the drying out of the surface soil layer the vine-plant starts to use moisture from deeper soil layers.

As a supplementation to the characteristics of the moistening for the microclimatological observation points the hydrothermical coefficient (HTC) has been calculated for the basic interphase periods in the greater part of the crop vegetation. Results are presented in *Table 4*.

Table 4. Mean values of the hydrothermic coefficient (HTC) during the different interphase periods of vinestock in the investigation period (1978-1980)

Plot points	Beginning of juice circulation – mass budding	HTC	Mass budding-mass dis-volving of leaves	HTC	Mass disvol-ving of leaves – mass blooming	HTC
2	21.03–09.04	1.73	09.04–28.04	1.67	28.04–13.06	1.50
0	20.03–10.04	1.55	10.04–30.04	1.96	30.04–12.06	1.47
6	20.03–12.04	1.58	12.04–01.05	1.67	01.05–11.06	1.49

Continuated Table 4

Mass blooming – mass beginning of ripening of grapes	HTC	Mass beginning of ripening of grapes – mass physiological ripeness	HTC
13.06–21.08	0.66	21.08–16.09	1.30
12.06–20.08	0.64	20.08–14.09	1.41
11.06–19.08	0.65	19.08–11.09	1.47

The analysis of the table allows us to state that during the investigation period the vineyards, situated in the hilly relief, were well supplied with soil moisture.

In the first three interphase periods the moistening in all points of the relief had a HTC over 1.0. It was especially high in the second interphase period i.e. from the mass budding to the mass unfolding of the leaves. The lowest HTC was in the fourth interphase period i.e. from the mass blooming to the beginning of the mass ripening of grapes. It is obvious that such a distribution of the HTC during the vegetation periods is explained by the precipitation and temperature regime and only the taking into consideration of these two factors allows to speak about air dryness of the development period of grape-vine.

The water consumption coefficient (Cw) is a microclimatic index, which is in fact a ratio of the vineyard's water consumption of the points on the slopes to the standard — the valley (point 6) (*Table 5*). In Table 5 it can be seen that the values of Cw differ slightly. For the slopes, generally taken, a higher total water consumption is characteristic in comparison with the valley excepting of point 3, because of the little width of the soil profile, the soil type and the peculiarities of the moistening regime there.

Table 5. Mean values of the total water consumption coefficient (Cw) in the different months, seasons and for the whole warm period during the investigation (1978-1980)

Plot points	Apr	May	Jun	Jul	Aug	Sep	Oct	Apr–May	Jun–Aug	Sept–Oct	Apr–Oct
2	0.89	0.87	0.91	0.74	1.12	1.07	1.08	0.88	0.91	1.07	0.93
3	0.73	0.46	0.42	0.47	0.73	0.75	0.79	0.58	0.52	0.76	0.58
6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	0.99	1.02	1.01	0.91	1.12	1.24	1.29	1.01	1.00	1.25	1.05

The soil moisture regime together with the thermic conditions are deciding for the achievement of high yields of excellent grape berry quality. The parallel observations made during the period of investigation in connection with the quality and quantity of the yields of Bolgar grapes variety grown under the different conditions of the experiment have shown that the highest yields were in the valley. While the quantity of bunches of grapes per vine-bush in all the three sections (plots) was the same (19), the mass of one cluster was 300 g at point 2, 402 g at point 3 and 426 g at point 6 as an average; the mass of 100 grapes was 394, 439 and 516 g in the very same points, respectively; grape-yields from one bush — 5.4, 7.3 and 8.1 kg and the yield of grapes from one hectare — 1.3, 1.7 and 1.9 ton. The quality of the yields, however, has an inverse dependence: the biggest quantity of sugar content (17%) and the lowest quantity of acids (5.6%) in grapes are observed in the middle part of the slope, followed by its lower part — 16.7% and 5.7% and the valley — 15.5% and 5.9% (*Babrikov et al.*, 1981).

4. Conclusions

(1) Under the conditions of the experiment the grape-vines are well supplied with moisture from the beginning of the vegetation period to the end of blooming. In the rest of the vegetation period the soil moisture content in the 1 meter layer is mostly below the optimum particularly in the valley but here the vine-plant retrieves the lack of moisture from the soil layers laying below.

(2) The soil moisture content is at its highest value at the beginning of vegetation, then decreases continuously and its value is at the minimum in the beginning of autumn. With the transition of the vine stock from vegetation to a quiet condition and the increase of the precipitation amount in autumn the accumulation of soil moisture content starts.

(3) The water consumption of the vineyard without irrigation depends directly on the amount of rainfall during the vegetation period. As a whole, for the 'budding – physiological ripeness' period the water consumption of the vineyards on the slopes amounts to 363–396 mm and to 358 mm in the valley. The 24-hour maximum of water comsumption amounts to 2.7–3.2 mm from the 0–50 cm soil layer and to 3.0–3.5 mm from the 0–100 cm soil layer in the period near and after vine blooming.

(4) The analysis of meteorological, agrometeorological and biological factors affecting the vine growth and grape yields leads us to the well founded conclusion that on the North-Rhodopean slope the most favourable conditions for achieving comparatively high yields with a high quality of grapes exist at sections of the slope to be found at a 40–70 m vertical displacement from the bottom of the valley.

References

A Guide for Agrometeorological Observations, 1960: (ed.: *At. Vangelov*) (in Bulgarian), Hydrol. and Meteorology Office, Sofia.

Babrikov, D., *Braykov D.* and *Pandeliev, S.*, 1981: *Agricultural and Biological Aspects of the Problem about the Grape-vine Yields Forecasting*. Scientific Report (in Bulgarian). HAI *V. Kolarov*-Plovdiv.

Dabov, L., 1971: *A Manual for Meteorological Observations* (in Bulgarian). Hydrology and Meteorology Office, Sofia.

Fursa, D.I., 1986: *Weather, Irrigation and Vine Productivity* (in Russian). Gidrometeoizdat, Leningrad.

Magrisso, Yu., 1970: *Water Regime and Irrigation of the Grape-vine* (in Bulgarian). Publ. Bulgarian Acad. of Sciences, Sofia.

Onchev, N., 1974: *Draining Collectors and Channel-terraces for the Prevention of Erosion* (in Bulgarian). Ministry of Agric. and Food Ind., Sofia.

Stoychev, St. and *Dimov, D.*, 1986: *Some Peculiarities of the Distribution of Soil Moisture in Grape-vine Plantations Grown under the Conditions of the Hilly Relief of the North-Rhodopean Foothill Region* (in Bulgarian). Physics and Agriculture Production (Collected Articles), p. III., 452-457, Sofia.

Turmanidze, T.I., 1981: *Climate and Vine Crops* (in Russian). Gydrometeoizdat, Leningrad.

Winkler, A.I., 1962: *General Viticulture*. UCLA Press, Los Angeles.

NEWS

The Hungarian Meteorological Service was founded 125 years ago

On the 3rd of May, 1995, the Hungarian Meteorological Service (HMS) celebrated the 125th anniversary of its establishment. In the ceremony participated *Mr. Ferenc Baja*, Minister of Environmental Protection and Regional Development. 25 years ago a detailed account was published covering the first century of the history of the HMS. As a continuation, recently a similar volume was prepared for the period of 1971–1995. Furthermore, a more concise historical reviews written by *Prof. Rudolf Czelnai*, has just been published. This book does not deal with the technical details, its purpose is to give a broad overview from the very beginnings. To give a short insight into the history of the HMS, the summary of this latter book (125 Years of the Hungarian Meteorological Service) is quoted below:

» Preconditions and antecedents

Sporadic Hungarian records relating to weather go back to the 11th century. From 1540 there is some record for every year. The first instrumental observations in Hungary were initiated by Ádám Gensili in Sopron, in 1717. Climatic conditions relating to viticulture were recorded, along with phenological observations of vine, by the town-councillors of Kőszeg, starting from 1740 through some 200 years. One of the stations of the famous meteorological network of the Societas Meteorologica Palatina was established in Buda in 1780. (There were only 8 stations that remained operational through the whole period of the existence of the Society, and Buda was one of those.)

The development of a Hungarian technical language for meteorology began in the early 19th century, and by 1870 it was mature enough to allow an accurate translation of any foreign technical texts into clear Hungarian. By that time there was already an increasing public demand for meteorological information in the country.

Two important antecedents played a direct role in the creation of the Hungarian institute. Firstly, the Austrian 'Zentralanstalt für den meteorologischen und magnetischen Dienst' (one of the oldest such institutes in the world) was founded in 1851, and thereby an example was set. Secondly, the Hungarian Academy of Sciences was established in 1827, and (following the Austrian scenario) the proposal for the creation of the meteorological institute came from the Academy.

Beginning and early development (1870-1919)

A sparse network of meteorological stations had been organized in Hungarian territory by the Austrian institute and, therefore, Guido Schenzl, upon his appointment to the post of director was in the position to take over a core network from Carl Jelinek, director of the Austrian institute. Schenzl's most urgent tasks were to accelerate the further development of the network and to organize the processing and publication of the data. He accomplished both tasks in the most praiseworthy manner.

The time was favourable. In 1870 a vigorous modernization effort commenced in the whole Central-European area. It was a period of rapid growth and of a seething intellectual life. Guido Schenzl was in office just in time to participate at the International Meteorological Congress in Vienna (from 2 to 16 September 1873), where the International Meteorological Organization was created. Thus, Hungary was one of the 20 founding countries of the predecessor of the World Meteorological Organization (WMO).

'The inspiration for the remarkable enterprise known as the First International Polar Year (1882-1883) has to be attributed to the foresight and determination of Karl Weyprecht, a navigation officer of the Austro-Hungarian Navy' (Steinhauser, 1994). This internationally co-ordinated research programme set the example for some later similar enterprises, including the large-scale experiments of the Global Atmospheric Research Programme (GARP) of the International Council of Scientific Unions (ICSU) and WMO.

In 1890 Dr. Miklós Konkoly-Thege, the famous astrophysicist of the time, and an exuberant personality, was appointed to the post of director of the Hungarian institute. A prominent task for the meteorological institute in that period was to assist the accomplishment of one of the largest scale water regulation projects in history (more than 30 thousand square kilometres were to be reclaimed from marshes). This provided a good argument for the transfer of the institute from the Ministry of Education to the Ministry of Agriculture. The change resulted in a significant improvement in funding of the development of meteorological activities. By 1911 the Hungarian meteorological institute moved into its impressive new headquarters building. The professional work was done according to world standards. International connections were excellent and wide-ranging. There was a particularly close co-operation between the Hungarian institute and the meteorological observatory in Belgrade (this was due to a deep personal friendship between Konkoly-Thege and Milan Nedelkovich).

Between two wars, and after (1919-1950)

In the years following the First World War professional perspectives had been dramatically reduced. International connections became scarce, and funding insufficient even for a very limited scope of activities. Outstanding meteorologists went abroad: Aurél Anderkó was invited to Poland to assist in the organization of the meteorological service of the newly independent country; Antal Réthly was invited to Turkey for doing the same.

The only area, where something special was perhaps achieved, was upper-air research. Alfréd Hille carried out, between 1925 and 1943, altogether 1380 instrument flights with light aircraft. Géza Tóth, among other things, managed to make one of the earliest jetstream observations using traditional pilot balloon techniques. Thus there was some progress, but in relative terms the institute sank far below the professional world level.

The catastrophe that fell upon Hungary was manifold. The nation could not even recover from the consequences of the First World War, when came the second: the monstrosities of the holocaust and the total devastation of the country. The meteorological institute was not directly affected almost until the end of the war. But during the 51 days siege of Budapest the headquarters building of the institute was partly destroyed. After the communist take-over in 1948 (until then there was at least formally a parliamentary democracy) the professional staff was put under heavy pressure by a political commissar imposed upon the institute. During the night of 13 June, 1950, the director, Dr. Géza Tóth was arrested by the state security forces (as 'enemy of the state') and was interned to Recsk (the Hungarian gulag) until 1953 (when the whole prison-camp was abolished).

The 'socialist attempt at modernisation' (1950-1988)

In a way cold war helped. The threat of a military conflict made meteorology important. The supreme command could not afford shambles in the meteorological service. The institute was transferred to the Ministry of Defence and Lieutenant-Colonel Frigyes Dési was appointed director. He was a good scientist and a technocrat, but he had to make compromises with the leaders of the local organs of the communist party and the trade union (all of whom were non-professional staff members). He applied the Homeric principle of the 'lesser evil': yielded in many short-term affairs, but kept his hands free in the long-term issues of manpower development and international co-operation.

A meteorological faculty was created at the Eötvös Loránd University of Budapest shortly after the war in 1945. Beginning from 1950 a high number of students were enroled. Although many of them dropped out, diplomas in meteorology could be conferred upon altogether 113 young men and women between 1954 and 1957. In the field of education the success is unquestionable. Although the numbers of enrolments had to be reduced later, the quality of the education steadily improved, which fact is demonstrated again and again by the successes of young Hungarian meteorologists abroad.

International co-operation was another major focus. When it came to defend professional positions against narrow-minded political considerations, international requirements and standards offered the obvious argument. This has become particularly important after the Hungarian revolution in 1956, from which the lesson was learned that the West would not help, Hungarians must manage the situation and find the ways to make the best of it.

In 1968 the institute was transferred under the supervision of the National Council for Technical Development. The leadership of that organization was in the good hands of clear thinking technocrats. From that time onwards, through several years, the meteorological institute received a support unprecedented in its history.

The institute was transformed to become the Hungarian Meteorological Service (HMS) with three decentralized institutes belonging to it. A meteorological computer center (based on a Hungarian made EMG-830 processor) was established in 1970 and an IBM-System-7 telecommunication center in 1976. A number of specialized observatories were built and the scope of meteorological services was vastly expanded. One feature of this development was that in the spirit of the 'new economic mechanism' (an attempt to mix planned economy with some elements of market economy) commercial meteorological services were introduced. The development in this area was much faster than expected and around 1986 almost 60 per cent of the total financial support of the HMS came from extrabudgetary sources. This has become soon a major cause of concern.

Crisis and change (years after 1988)

In April 1988 the HMS was transferred to the Ministry of Environment and Water Management. Increasing financial difficulties caused that between 1990 and 1992 some 60 per cent of the staff had to be dismissed. There was also a need for a re-structuring in order to transform the Service into a western type public organization. In this new structure a separate 'commercial division' was created, which now has to finance itself from its own income. Having done all this streamlining, the HMS has left behind — we all hope — the inevitable phase of 'creative destruction'.

The most positive aspect of all recent changes is the very substantial and rapid technical development that has been accomplished since 1991. The HMS now has a highly advanced telecommunication system and an ETHERNET computer network within its own premises, consisting of 11 servers and more than 250 workstations. This system is connected — through a CISCO 4000 router — to the world-wide INTERNET computer network, to the European Center for Medium-range Weather Forecasting (ECMWF) in Reading, to the Lake Balaton Storm Warning Center at Siófok and to the LACE system in Vienna. Linkages to the Global Telecommunication System of WMO, to the aeronautical meteorological network (MOTNE) and to a number of users in Hungary and abroad is ensured through a UNIX-based dual NetSys 9700 telecommunication computer. In conclusion it may be stated with absolute certainty that the HMS is fully prepared to join the European systems both regarding its professional staff and its technical facilities.

Optimistic epilogue

The current political key word in Hungary is 'Europe'. Hungarians want to find the way back to the values of the successful/victorius West. The whole country wants to be prepared for joining the European systems as soon as possible. At least the HMS has done its home work.«

G. Major

Festive session of Meteorological Department Eötvös Loránd University, Budapest, Hungary

A special session was held at Eötvös Loránd University on 3 May 1995, on the occasion of the 50th anniversary of the foundation of the Meteorological Department.

Meteorologists and non-meteorologists, representatives of Eötvös Loránd University, Hungarian Academy of Sciences, Department of Climatology József Attila University (Szeged, Hungary), Department of Meteorology Kossuth Lajos University (Debrecen, Hungary), Debrecen Agricultural University, Hungarian Meteorological Service, Hungarian Meteorological Society, Meteorological Service of Hungarian Army, Department of Civil Engineering Nebraska-Lincoln University (U.S.A.), Meteorological and Geophysical Department Zagreb, University Croatia were present.

Festal address was delivered by *Prof. Ferenc Rákóczi*, head of the celebrating department, with the title of 'Past creating future'. A summary of the address is given below. The idea of the establishment of the Meteorological Department arose far before its realisation. The first meteorological lectures related to geography were given by *Lajos Lóczy, Radó Kövesligety, Géza Czirbusz, Jenő Klupáthy* at around 1920 , however no independent meteorological department was created at the time. Some 20 years passed, when finally a decision was made and published in the Hungarian Bulletin, on 11 November 1945, stating that 'by approval of Council of Ministers *Dr. József Száva-Kovács*, university professor is appointed to the Department of Atmosphere and Climatology, Philosophical Faculty of Pázmány

Péter University'. On 16 May 1949 the university was reorganised and the Meteorological Department became part of the newly created Faculty of Natural Sciences. Education of meteorologists started only in 1950. The staff of the first Meteorological Department were as follows: *József Száva-Kovács, Zoltán Dobosi, Zoltánné Dobosi, István Dvorcsák, Tamás Révész*. Some years later *László Erdős* and *László Felméry* joined and a curriculum was elaborated, some elements of which are still used in the present education. The period of training of meteorologists was 4 years.

From 1953 until 1972 *Frigyes Dési* was the head of department. In 1957 the education period was extended to 5 years, which is still valid. The education system was changed: no 'independent' meteorologists were educated, but undergraduates studying on the faculty of mathematics, physics and geography could join the meteorological training and finally receive a double diploma. From 1980/81 the earlier system was restored, with some modifications of curriculum. Only one diploma, i.e. that of 'meteorologist' was released, however new subjects such as numerical forecasting, satellite meteorology, environmental protection, computer technics were introduced. The high level of education was admitted by WMO, as well. Between 1972 and 1983 Zoltán Dobosi led the department. In 1983 *Ferenc Rákóczi* was appointed to the leading post. From 1993 another new system of education was introduced: postgraduate course was organised, the educational period for achieving Ph.D. degree is 3 years.

Beside their educational activity, the staff of the department carry out scientific research in various fields, such as dynamical meteorology, climatology, agrometeorology, information theory, planetary boundary layer, meteorological application of statistical meteorology. Researches related to topical problems such as theory of forecast, climate change and environmental protection are also being made.

The Meteorological Department has widespread internal and international connections. It has close relation with the Hungarian Meteorological Service and also with the Meteorological Service of Hungarian Army, for which several courses are organised. International relations are also fruitful with Meteorological Departments of various universities. Close co-operation exists with the universities of St. Petersburg, Zagreb, Wien, Sofia, Padova, Berlin, München, Bratislava, Nebraska and Seattle.

In conclusion *Ferenc Rákóczi* expressed his conviction that the Meteorological Department of Eötvös Loránd University would form young meteorologists of high knowledge in the future as well.

At the end of the celebration participants greeted the department. The festive mood was enhanced by Orchestra of Eötvös Loránd University performing a splendid musical composition of Handel.

Zs. Iványi

ATMOSPHERIC ENVIRONMENT

an international journal

To promote the distribution of Atmospheric Environment *Időjárás* publishes regularly the *contents* of this important journal. For further information the interested reader is asked to contact *Dr. P. Brimblecombe,* School for Environmental Sciences, University of East Anglia, Norwich NR 7TJ, U.K.

Volume 29 Number 4 1995

Volume 29 Number 5 1995

Volume 29 Number 6 1995

Volume 29 Number 7 1995

NOTES TO CONTRIBUTORS

The purpose of *Időjárás* is to publish papers in the field of theoretical and applied meteorology. These may be reports on new results of scientific investigations, critical review articles summarizing current problems in certain subject, or shorter contributions dealing with a specific question. Authors may be of any nationality but papers are published only in English.

Papers will be subjected to constructive criticism by unidentified referees.

* * *

The manuscript should meet the following formal requirements:

Title should contain the title of the paper, the names(s) of the author(s) with indication of the name and address of employment.

The title should be followed by an *abstract* containing the aim, method and conclusions of the scientific investigation. After the abstract, the *key-words* of the content of the paper must be given.

Three copies of the manuscript, typed with double space, should be sent to the Editor-in-Chief: *P.O. Box 39, H-1675 Budapest,* Hungary.

References: The text citation should contain the name(s) of the author(s) in Italic letter or underlined and the year of publication. In case of one author: *Miller* (1989), or if the name of the author cannot be fitted into the text: *(Miller,* 1989); in the case of two authors: *Gamov* and *Cleveland* (1973); if there are more than two authors: *Smith et al.* (1990). When referring to several papers published in the same year by the same author, the year of publication should be followed by letters a,b etc. At the end of the paper the list of references should be arranged alphabetically. For an article: the name(s) of author(s) in Italics or underlined, year, title of article, name of journal, volume number (the latter two in Italics or underlined) and pages. E.g. *Nathan, K. K.,* 1986: A note on the relationship between photosynthetically active radiation and cloud amount. *Időjárás 90,* 10-13. For a book: the name(s) of author(s), year, title of the book (all in Italics or underlined with except of the year), publisher and place of publication. E.g. *Junge, C. E.,* 1963: *Air Chemistry and Radioactivity.* Academic Press, New York and London.

Figures should be prepared entirely in black India ink upon transparent paper or copied by a good quality copier. A series of figures should be attached to each copy of the manuscript. The legends of figures should be given on a separate sheet. Photographs of good quality may be provided in black and white.

Tables should be marked by Arabic numbers and provided on separate sheets together with relevant captions. In one table the column number is maximum 13 if possible. One column should not contain more than five characters.

Mathematical formulas and *symbols:* non-Latin letters and hand-written marks should be explained by making marginal notes in pencil.

The final text should be submitted both in manuscript form and on *diskette.* Use standard 3.5" or 5.25" DOS formatted diskettes for this purpose. The following word processors are supported: WordPerfect 5.1, WordPerfect for Windows 5.1, Microsoft Word 5.5, Microsoft Word 6.0. In all other cases the preferred text format is ASCII.

* * *

Authors receive 30 *reprints* free of charge. Additional reprints may be ordered at the authors' expense when sending back the proofs to the Editorial Office.

Published by the Hungarian Meteorological Service

Budapest, Hungary

INDEX: 26 361

HU ISSN 0324-6329

IDŐJÁRÁS

QUARTERLY JOURNAL
OF THE HUNGARIAN METEOROLOGICAL SERVICE

Greenhouse Gas Emissions And Response Policies In Central And Eastern Europe

Proceedings of the Workshop
Budapest, Hungary 11-14 May 1995

VOL. 99 * NO. 3-4 * JULY-DECEMBER 1995

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

Editorial Office: P.O. Box 39, H-1675 Budapest, Hungary or
Gilice tér 39, H-1181 Budapest, Hungary
E-mail: gmajor@met.hu; Fax: (36-1) 290-7387

Subscription from customers in Hungary should be sent to the Financial Department of the Hungarian Meteorological Service, Kitaibel Pál u. 1, H-1024 Budapest.

Abroad the journal can be purchased from the distributor: KULTURA, P.O. Box 149, H-1389 Budapest.

NOTES TO CONTRIBUTORS

The purpose of *Időjárás* is to publish papers in the field of theoretical and applied meteorology. These may be reports on new results of scientific investigations, critical review articles summarizing current problems in certain subject, or shorter contributions dealing with a specific question. Authors may be of any nationality but papers are published only in English.

Papers will be subjected to constructive criticism by unidentified referees.

* * *

The manuscript should meet the following formal requirements:

Title should contain the title of the paper, the names(s) of the author(s) with indication of the name and address of employment.

The title should be followed by an *abstract* containing the aim, method and conclusions of the scientific investigation. After the abstract, the *key-words* of the content of the paper must be given.

Three copies of the manuscript, typed with double space, should be sent to the Editor-in-Chief: *P.O. Box 39, H-1675 Budapest,* Hungary.

References: The text citation should contain the name(s) of the author(s) in Italic letter or underlined and the year of publication. In case of one author: *Miller* (1989), or if the name of the author cannot be fitted into the text: *(Miller,* 1989); in the case of two authors: *Gamov* and *Cleveland* (1973); if there are more than two authors: *Smith et al.* (1990). When referring to several papers published in the same year by the same author, the year of publication should be followed by letters a,b etc. At the end of the paper the list of references should be arranged alphabetically. For an article: the name(s) of author(s) in Italics or underlined, year, title of article, name of journal, volume number (the latter two in Italics or underlined) and pages. E.g. *Nathan, K. K.,* 1986: A note on the relationship between photosynthetically active radiation and cloud amount. *Időjárás 90,* 10-13. For a book: the name(s) of author(s), year, title of the book (all in Italics or underlined with except of the year), publisher and place of publication. E.g. *Junge, C. E.,* 1963: *Air Chemistry and Radioactivity.* Academic Press, New York and London.

Figures should be prepared entirely in black India ink upon transparent paper or copied by a good quality copier. A series of figures should be attached to each copy of the manuscript. The legends of figures should be given on a separate sheet. Photographs of good quality may be provided in, black and white.

Tables should be marked by Arabic numbers and provided on separate sheets together with relevant captions. In one table the column number is maximum 13 if possible. One column should not contain more than five characters.

Mathematical formulas and *symbols:* non-Latin letters and hand-written marks should be explained by making marginal notes in pencil.

The final text should be submitted both in manuscript form and on *diskette.* Use standard 3.5" or 5.25" DOS formatted diskettes for this purpose. The following word processors are supported: WordPerfect 5.1, WordPerfect for Windows 5.1, Microsoft Word 5.5, Microsoft Word 6.0. In all other cases the preferred text format is ASCII.

* * *

Authors receive 30 *reprints* free of charge. Additional reprints may be ordered at the authors' expense when sending back the proofs to the Editorial Office.

Greenhouse Gas Emissions and Response Policies in Central and Eastern Europe

Greenhouse Gas Emissions and Response Policies in Central and Eastern Europe

Budapest, Hungary, 11–14 May 1995

Edited by:

Gregg Marland
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge Tennessee 37831-6335, USA

Sándor Molnár
SYSTEMEXPERT Consulting Ltd.
Mikoviny S. u. 2-4, H-1037 Budapest, Hungary

Alexei Sankovski
ICF, Inc. 1850 K Street, NW, Suite 1000, Washington DC, 20006, USA

Joe Wisniewski
Wisniewski & Associates, Inc.
6862 McLean Province Circle, Falls Church, VA, 22043, USA

***

Executive Editor

Margit Antal
Hungarian Meteorological Service

Published by the Hungarian Meteorological Service
Budapest

The information in this document has been subjected to technical review, but does not necessarily reflect the official views of any governmental or intergovernmental body

Published by the Hungarian Meteorological Service, Budapest

Editorial Office: *P.O. Box 39, H-1675 Budapest, Hungary*
Fax: (36-1) 290-7387
E-mail: gmajor@met.hu

Printed in Hungary at the Pátria Press

ISBN 963 7702 63 6 hardback
ISBN 963 7702 64 4 paperback
INDEX: 26 361
HU ISSN 0324-6329

Copies of this book may be obtained from Jack Fitzgerald, U.S. Country Study Management Team, 1000 Independence Ave., S.W. PO-63, Room 4G-036, Washington, D.C. 20585, USA (Phone: 202-426-0194; Fax: 202-426-1540) and from G. Major, Editor-in-Chief, Hungarian Meteorological Service, H-1675 Budapest, P.O. Box 39, Hungary (Phone/Fax: (361) 290-7387, E-mail: gmajor@met.hu).

Contents

PART II: Greenhouse Gas Emissions in Countries of Central and Eastern Europe and Newly Independent States

PART III: Mitigating the Climate Change: Examples of Response Policy

Foreword

The ultimate objective of the Framework Convention on Climate Change (FCCC) is the stabilization of atmospheric concentrations of greenhouse gases, but a number of important problems remain to be solved before a target stabilization level can be quantitatively specified. What *can* be calculated with some confidence is that current emissions from human activities are likely to lead to increasing atmospheric concentrations of these gases over coming decades or even centuries. Whatever route is eventually chosen to meet the Convention's ultimate objective, systematic quantification of present day anthropogenic emissions, using comparable methods, is a necessary basis for international agreements on future emissions.

Once compiled, a national greenhouse gas inventory serves as a valuable tool within the context of the Climate Convention. It allows each country to place its own emissions within the larger picture of global emissions, and provides a baseline against which its own future emissions can be compared. It also provides a basis for the formulation of a national greenhouse gas mitigation policy. Furthermore, experience shows — and the studies reported here are no exception — that compilation of the inventory brings additional benefits, including improved national statistics, increased awareness of the issues surrounding climate change among government and industry, and improved cooperation between countries with similar patterns of greenhouse gas emissions.

The US Country Studies Program uses the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories as its standard inventory methodology. The Guidelines currently represent the only inventory methodology specifically accepted by the Parties to the Climate Convention. Developed over three years under a program coordinated jointly by IPCC, the Organization for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA), the Guidelines provide an internationally-accepted methodology for quantifying emissions of carbon dioxide, methane and nitrous oxide. Methods and default data contained in the Guidelines are based on wide international consultation and on the best information available in the scientific and technical literature. Nevertheless, the development of the Guidelines must be seen as an ongoing process, and the studies reported in this workshop represent searching tests of the practical applicability of the Guidelines as well as important sources of guidance for future improvements.

Under the IPCC Guidelines, the basic approach for calculating emissions of a particular gas from a particular sector or sub-sector is simple in concept:

$$\text{Emissions} = \text{Base year activity level} \times \text{Emission factor.}$$

However, determining appropriate activity levels and emission factors can become somewhat difficult. A particular feature of greenhouse gas emissions in Central and Eastern Europe is the high proportion that comes from energy and industrial sectors, which are currently undergoing dramatic changes due to the shift from a centrally-planned to a free-market national economy. In general, these changes have led to a significant decline in energy and industrial production, which started in 1988–1990 and continues in many Central and Eastern European countries. Economic changes also reduced the availability and quality of centralized energy and industrial statistics, since many newly privatized enterprises treat production volumes as confidential information. Papers presented in this book discuss trends in national greenhouse gas emissions during the period of economic transition and evaluate uncertainty of initial activity data. In addition, many authors raise the issue of the base year that should be used to develop national emission-reduction targets. For many Central and Eastern European countries, 1990, which is selected as a base by the IPCC, is a very atypical year because it was characterized by significant economic decline and corresponding drop in emission volumes.

It is very important to acknowledge the coordinating and facilitating role played by the various country study programs related to the Climate Convention, including the US Country Studies Program. Through input of resources and collaborative efforts, these programs supported the original development of the IPCC Guidelines, helped to achieve their wide international acceptance, and contributed to their final publications. In addition, country case study programs that have used the IPCC methodology have been instrumental in delivering the IPCC manuals, and providing training to a large number of developing countries and countries with economies in transition. The substantial progress in the compilation of national greenhouse gas inventories that is reflected by papers published in this book represents some of the rewards of these extensive international efforts.

Bruce Callander
IPCC Scientific Assessment Working Group
Intergovernmental Panel on Climate Change
Meteorological Office, Hadley Climate Centre
London Road, Bracknell
RG12 2SY, United Kingdom

Preface

Understanding the role of greenhouse gas emissions in the global atmospheric system has become a crucial item as policy makers consider options to mitigate anticipated adverse effects of climate change. Sound data and scientific information are critical in understanding how climate may respond to human actions.

To achieve this understanding a series of regional workshops on greenhouse gas emission inventories are being held throughout the world during 1995. The main goal of each of these workshops is to help facilitate development of country-specific greenhouse gas emissions inventories, as required by the Framework Convention on Climate Change. The workshops are intended to provide an international forum for the exchange of information among representatives of countries undertaking climate change country studies, researchers and experts on greenhouse gas emissions, and policy makers. At the workshops, participants present results of their inventory work and discuss issues related to greenhouse gas emission estimation methodologies. Presentations on both methodological issues and results of national assessments are organized into numerous sectors, namely: fossil fuel combustion for energy; energy production, transmission and distribution; industrial processes; waste management; agriculture; and forestry and land use change. In addition to presenting papers, workshop participants break into working groups to discuss methodological questions and develop practical recommendations.

More specifically, the workshop's goals/objectives are as follows:

- Promote the exchange of information on participant's experience in preparing inventories and provide a forums for constructive discussion of available methodologies among country researchers and international experts.

- Further the development of a consensus on methods for improving the quality of input data and emission estimates.

- Identify and discuss possible options for cooperation and coordination among countries and institutions involved in climate change studies.

During 8–11 May 1995, the Central and Eastern European Workshop on Greenhouse Gas Emission Inventories and Response Policies was held in Budapest, Hungary. This workshop was jointly organized and sponsored by the U.S. Country Study Program and the Dutch-Hungarian Bilateral Cooperation Project on Climate Change. The workshop's hosts were the Hungarian Ministry for Environment and Regional Policy, and the Hungarian Electrotechnical Association, Systemexpert Consulting Ltd. Over 60 scientists from virtually all

Central and Eastern Europe including the newly independent countries of the former Soviet Union gathered together. The workshop was also attended by emission inventory experts from the USA, the Netherlands, France and Germany. Over 30 presentations were made and 28 peer reviewed papers including the Workshop Overview Summary appear in this volume.

A central element of the Budapest workshop was the IPCC Guidelines for National Greenhouse Gas Inventories[1]. In addition, participants of the workshop discussed policies and measures focused on reducing greenhouse gas emissions.

The IPCC Guidelines were originally conceived by the Organization for Economic Cooperation and Development (OECD) as a means to encourage member countries to produce inventories of greenhouse gas emissions that are consistent, comparable, and mutually transparent among countries. Over three years this set of guidelines evolved through collaboration with the IPCC, the International Energy Agency, the World Meteorological Organization, the United Nation Environment Programme, and expert workshops and consultations. It now provides, in three volumes, a basis for all countries to compile the emissions inventories that are required by the Framework Convention on Climate Change.

The IPCC Guidelines are limited both by scientific understanding and by lack of experience with their application. Problems of the first type will be approached by scientific investigations around the world. Problems of the second type will be resolved with time and experience and with the kinds of interchange and collaboration that flow from workshops such as the one in Budapest. Such workshops aim not only to produce inventories of greenhouse gas emissions but to enlarge our collective understanding of the ways, places, and rates in which greenhouse gases are emitted to the atmosphere. The workshop was to challenge the comprehensiveness and generality of the guidelines and their ability to produce emission inventories that are scientifically sound, technically useful, and politically appropriate. In this workshop, the countries of Central and Eastern Europe reported their initial experiences with emissions inventories for greenhouse gases and also sought to improve the international guidelines by examining where they were deficient, inappropriate, or needing clarity or definition. Part I of this volume is devoted to methodological issues of estimating greenhouse gas emissions, while Part II provides country-specific estimates of emissions from various sectors of economic activity.

Describing greenhouse gas emissions at the national level provides a basis for developing policies and measures to reduce these emissions in the future. Participants of the workshop discussed emission reduction measures developed

---

[1] IPCC Guidelines for National Greenhouse Gas Inventories, 1995. United Nations Environmental Programme (UNEP), the Organization for Economic Cooperation and Development (OECD), the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change, Vol. 1–3.

in the framework of the Dutch-Hungarian Bilateral Cooperation Project on Climate Change. Part III of this volume describes results of modelling impacts of emission reduction measures and discusses the process of negotiating action programs to reduce emissions.

While much of the workshop was devoted to preliminary results and methodologies, we feel that discussions and professional interaction at the workshop have greatly enhanced our understanding of the Central and Eastern European contribution to the global greenhouse gas balance. As such, we look at this as the start of a process to continue to learn in this region.

Gregg Marland
Sándor Molnár
Alexei Sankovski
Joe Wisniewski

Acknowledgements

We acknowledge the individual contributions of the workshop participants, who presented results of their findings during workshop plenary sessions and played an active role in the working group discussions. Scientists, experts and state officials attending the meeting were instrumental in examining the role of Central and Eastern European countries in forming the global greenhouse gas balance and exploring region-specific measures to mitigate climate change.

Our special thanks to the U.S. Country Studies Program, which was a major sponsor of the Budapest Workshop. Members of the Country Study Management Team, Robert Dixon (director) and Jack Fitzgerald, were instrumental in ensuring that the meeting was a successful step toward developing comprehensive greenhouse gas inventories in Central and Eastern European countries and that results of these inventories are available to international experts and policy makers. We acknowledge the support of the Dutch Ministry of Housing, Spatial Planning & the Environment (represented at the workshop by Wim Iestra), the Hungarian Ministry for Environment & Regional Policy (represented at the workshop by Tibor Faragó, Csaba Nemes and Tamás Pálvölgyi), and the Systemexpert Consulting Ltd. (represented at the workshop by Sándor Molnár and Tibor Takács).

We would like to thank Craig Ebert, Sándor Molnár, Tibor Faragó, Frank Rijsberman, Nina Radics, Alissa Strauss, Nelly Szkok, Tibor Takács, and Rolien Wams for organizing and coordinating the workshop.

A vital assistance in developing a publication strategy and preparing the workshop results for publication was provided by William Driscoll of ICF and EMR consultants. Preliminary formatting and editing of the workshop materials was conducted with the support of Emily Barnett, Therese Fela, Theresa Mertens, Cathleen Kelly and Alissa Strauss of ICF. A front cover was designed by John Paul McCarty (ICF).

Co-Editors:

Gregg Marland
Sándor Molnár
Alexei Sankovski
Joe Wisniewski

PART I

Methodological Aspects of Estimating Greenhouse Gas Emissions

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Greenhouse Gas Emissions and Response Policies in Central and Eastern Europe: Workshop Overview Summary

Gregg Marland[1], **Sándor Molnár**[2], **Alexei Sankovski**[3] and **Joe Wisniewski**[4]

[1]*Oak Ridge National Laboratory,*
P.O. Box 2008, Oak Ridge Tennessee 37831-6335, USA

[2]*SYSTEMEXPERT Consulting Ltd.,*
Mikoviny S. u. 2-4, H-1037 Budapest, Hungary

[3]*ICF, Inc. 1850 K Street, NW, Suite 1000, Washington D.C., 20006, USA*

[4]*Wisniewski & Associates, Inc.,*
6862 McLean Province Circle, Falls Church, VA, 22043, USA

Abstract—This paper is an overview of the main issues discussed in the workshop 'Greenhouse Gas Emissions and Response Policies in Central and Eastern Europe' held in Budapest, Hungary during 11–14 May 1995. Summaries, highlights, key points and recommendations are detailed with respect to greenhouse gas emissions from industry, solvents, waste, agriculture and land use. Policy Response issues are also discussed in the context of various emission strategies/scenarios.

1. Introduction

Understanding the role of greenhouse gas emissions in the global atmospheric system has become a crucial item as policy makers consider options to mitigate anticipated adverse effects of climate change. Sound data and scientific information are crucial in understanding how climate may respond to human actions. This paper summarizes the key conclusions, findings and recommendations from the Central and Eastern European Workshop on Greenhouse Gas Emission Inventories and Response Policies held in Budapest, Hungary during 1995. The methodological issues and results of national assessments are organized into numerous technical (e.g., fossil fuel production for energy, agriculture, land use) and policy response areas.

2. Greenhouse Gas Emissions from Energy, Industry, Solvents, and Wastes: Key Issues of Applying the IPCC Methodology in Central and Eastern European Countries, and the Newly Independent States

The dominant emission of greenhouse gases from most countries of Central and Eastern Europe is CO_2 from energy systems. While, this is a sector where inventories are most able to produce reasonable estimates of emissions, there are a variety of issues that lead to difficulties or create unique situations in compiling national inventories. For example, national statistical resources and key terminology may differ between participating countries. Also, unique economic or political circumstances may cause differences between emission estimation methodologies selected by individual countries. For other gases and other sectors, there is still much to be learned on how to best estimate emissions and on the quality of the ensuing estimates. Both the data on the magnitude of activities which emit gases and the factors which characterize emissions per unit of activity will be improved with additional activity-specific and site-specific data.

Importantly, participants in these discussions expressed a consensus that the IPCC Guidelines provide a reasonable basis and a set of first-order emission factors from which countries can begin to estimate emissions and to structure their reporting for transparency and comparability. Discussants agreed further that the Guidelines were supportive in encouraging inventories to rely on national data sources when they were available. They agreed to utilize and documenting these national resources if they offered insight or data beyond the default values suggested in the Guidelines. There was also consensus that the 'top-down' calculations based on national aggregate energy statistics provided a comprehensive estimate of national CO_2 emissions. However, for other gases and for information reflecting the structure and trends of the economy, which is required for evaluating the opportunities for emissions mitigation, the 'bottom up' calculations that rely on more detailed disaggregation of gas-emitting activities and technologies are needed.

Some of the additional issues that arose in group discussion are listed below. These ranged from reporting experiences in the inventory process to lengthy discussion on how specific issues might be dealt with or the IPCC Guidelines made more useable.

2.1 General Issues on Emission Inventories

- A discrepancy may exist between measurements of emission due to coal production because countries in Eastern Europe measure coal production before coal cleaning occurs, while countries of Western Europe and North America measure coal production after cleaning.

- It was recognized that a comparison of bottom-up and top-down calculations will fail to match when fuels change form, e.g. coke oven gas may be counted as a solid fuel in some accountings and as a gas in others.
- For some emissions estimates, it may be very expensive to obtain the requisite data or measurements.
- Analysts recognized that improving precision does not necessarily result in improvements in accuracy.
- Estimates of fugitive emissions from gas production and transport in Russia are being actively pursued but there is still considerable uncertainty as to its magnitude.
- For countries undergoing economic transition there may be a problem with emissions estimates when engineering systems are either totally shut down or not operating according to specifications.

2.2 Factors Not Dealt with in the IPCC Guidelines:

- Instances in addition to bunker fuels which involve emissions related to international commerce. For example, an international pipeline may cross a third-party state and have both leakage and consumption at compressor stations within the intervening state.
- How emissions generated by military personnel and installations that are outside of the parent country are both measured and mitigated.
- Oxidation of coal on mine tailings piles, a potentially large contributor of emissions in some places.

2.3 Factors applicable to specific countries

- Different countries, in their statistical bases, define economic sectors differently, e.g. the transportation sector.
- In many countries, national energy statistics may not distinguish all of the same fuel categories, transactions, or process steps considered in the IPCC Guidelines, e.g. bunker fuels are not always identified.
- The unoxidized fraction of fuels, particularly coal, may be very different in some locations and some sectors.
- The magnitude and distribution of non-fuel uses of petroleum liquids varies considerably among countries.

3. Greenhouse Gas Emissions From Agriculture and Land Use Change & Forestry: Key Issues of Applying the IPCC Methodology in Central and Eastern European Countries, and the Newly Independent States

Agricultural activities as well as changes in land use and forest structure were traditionally important sources of greenhouse gas emissions in countries of Central and Eastern Europe, including Newly Independent States (NIS). Most of these countries have a well-developed agricultural sector and significant forest resources. Better understanding of specific factors effecting agriculture and land use related emissions in Central and Eastern European countries will lead to a more accurate assessment of the region's input in the global greenhouse gas balance. The results of discussions in the working group on emissions from agriculture and land use change & forestry are summarized below.

3.1 Agriculture

The most important agricultural sources of greenhouse gases (GHG) in Central and Eastern European countries are: livestock (methane, CH_4) and agricultural soils (nitrous oxide, N_2O).

Methane emissions from agriculture comprise 20% of the total anthropogenic methane emissions in Bulgaria, about 24% in the Czech Republic, and about 26% in Kazakhstan. Nitrous oxide emissions from agricultural soils also significantly contribute to the national anthropogenic totals (e.g., in Bulgaria—up to 60%).

Emissions from livestock

Livestock produce methane emissions through their normal digestive processes (enteric fermentation) and through the anaerobic decomposition of their manure. The amount of methane produced by enteric fermentation depends upon the animal's digestive system and the amount and type of feed it consumes. Most of CH_4 from agriculture in Central and Eastern European countries is produced by different breeds of cattle. Methane emissions from anaerobic manure decomposition comprise from 20 (Kazakhstan) to 36 (Bulgaria) per cent of the total emissions from livestock. The principal factors affecting methane emissions from this source are the amount of manure produced and the portion of the manure that decomposes anaerobically. Commonly used anaerobic manure management systems in Central and Eastern European countries and NIS include lagoons, earthen basins and storage tanks.

- Major uncertainty associated with estimating emissions from livestock is caused by inaccuracy of national statistics rather than by inadequacy of the IPCC methodology.
- A 10% difference between estimates of methane emissions from livestock

obtained using the IPCC Tier 1 approach (based on global average values of emissions factors) and the IPCC Tier 2 approach (based on country-specific data) is generally acceptable.

- Based on results of their discussions, working group participants recommended that countries with large cattle populations (e.g., Russia, Ukraine) consider using the IPCC Tier 2 approach for estimating emissions from livestock.

Emissions from agricultural soils

Nitrous oxide (N_2O) in agricultural soil is produced primarily by the microbial processes of nitrification and denitrification. Emission rates depend on a wide variety of natural and cultivation processes. Individual factors that control nitrification and denitrification include: soil water content; temperature; nitrate and ammonium concentrations; available organic carbon; and pH.

- Since emissions of nitrous oxide from agricultural soils depend on many site-specific factors, countries are encouraged to use results of local and regional studies to derive appropriate emission coefficients. Countries might also use locally available data to account for emissions of other GHG gases from agricultural soils. This approach, for example, was adopted by Kazakhstan specialists (E. Gossen) to determine NO_x emissions from fertilizer use.
- Dramatic structural changes in Central and Eastern European countries have led to decreases in total consumption of nitrogen fertilizers. Also, agricultural producers in these countries are starting to use fertilizers more efficiently, which might eventually result in reduced emissions per unit of applied fertilizer.
- New agricultural sources of N_2O described by the Dutch experts (presented by Dr. C. Kroeze) also exist in some Eastern and Central European countries. For example, N_20 emissions from leakage of nitrogen from agricultural soils into ground water could potentially occur in Latvia and Estonia (due to relatively high soil percolation rates), while emissions associated with manure leakage from stables could reach substantial levels in Russia and Kazakhstan. These hypothesis, however, require further testing.

The following general issues should be considered while developing methods to estimate emissions from agriculture that are suitable for conditions in Central and Eastern Europe:

- On average, factors affecting greenhouse gas emissions from agriculture show significant variability across Central and Eastern Europe due to profound natural and economic differences among countries (e.g., intensive system of cattle management, which is typical in Central Europe is quite rare in Kazakhstan, where range-fed cattle predominate). This differentiation necessitate developing country- and site-specific methods of emission estimation.

- Dramatic economic changes in Central and Eastern European countries generally lead to a substantial decrease in quality and quantity of agricultural statistical data (e.g., national departments of agriculture are unable to collect information from a large number of newly-created private agricultural enterprises). Thus, it is recommended that countries evaluate accuracy of agricultural activity data using locally available information and assistance of professional statisticians.
- Quality of national inventories could be substantially improved if countries exchange information about emission sources not developed in the current IPCC Guidelines.

3.2 Land Use Change and Forestry

Estimating GHG emissions from land use change and forestry according to the current IPCC methodology is based on two major principles: (a) fluxes of CO_2 to and from the atmosphere are assumed to be equal to changes in carbon stocks in existing biomass and soil; and (b) changes in carbon stocks can be estimated by establishing rates of change in land use and then applying basic assumptions about greenhouse gas fluxes response for a given land use.

- The uncertainty of estimating GHG emissions from land use and forestry has several major sources: (a) default emission factors and coefficients provided in the IPCC Guidelines are highly aggregated estimates and do not adequately reflect environmental conditions in Central and Eastern European countries; (b) in some Central and Eastern European countries, official data on land use change and forestry activities are not always available and could be highly inaccurate; (c) some greenhouse gas sources and sinks from the 'Land use Change and Forestry' category (such as below ground biomass and soil) are not well developed in the current IPCC Guidelines.
- The current IPCC methodology should be directly applied to only those forests that change their carbon content due to specific anthropogenic activities. Some countries with significant forest resources face a problem of discriminating between managed and undisturbed forests and woodlands. One possibility for addressing this problem is to avoid dividing forests (and other ecosystems which could be treated as greenhouse gas sources and sinks) into 'managed' vs. 'undisturbed' categories (geographical approach) but instead separate *natural* and *man-induced* changes in forest growth and development within the same area ('Cause-Effect' approach). For example, in a specific tract of managed old growth forest, natural population cycles could account for 80% of all biomass stock changes, while activities oriented towards improving forest growth — for the remaining 20%.

- In some countries (e.g., Russia, Kazakhstan) spontaneous and prescribed forests fires lead to significant emissions of greenhouse gases. In Kazakhstan this source was described by applying the IPCC methodology, originally developed for estimating emissions from biomass burning. Emissions caused by fire in Kazakhstan were estimated separately for different forest types (fir, larch) and different types of post-fire regeneration (birch, aspen). It needs to be emphasized that only human-induced changes in fire regime (including fire suppression) should be included in national greenhouse gas inventories.
- Only forest and grassland ecosystems are explicitly addressed in the current IPCC methodology. Meanwhile, other ecosystem types such as wetlands, steppe, woodlands, rivers, and lakes could play important roles in greenhouse gas budgets of individual countries. An original approach to estimating emissions from wetlands is being developed in Estonia (A. Karindi), while Russia (A. Kokorin and I. Nazarov) is developing a methodology to quantify carbon sinks in boreal and temperate forests (forest types insufficiently addressed in the current IPCC Guidelines).
- The current IPCC Guidelines provide limited guidance for estimating emissions associated with changes in soil carbon content. Meanwhile, these emissions in temperate and boreal zones could account for a substantial portion of the terrestrial carbon flux. Since carbon content in soils and the rate of its change varies considerably from site to site, countries are encouraged to seek their own local estimates of these parameters and use them to estimate emissions.

4. Response Policies

Response policies were discussed in the working group with specific reference to the situation in Central and Eastern European countries. The discussion focused on three areas: overview of emission reduction measures; modelling impacts of emission reduction measures and strategies; and the process of negotiating action programs to reduce emissions. The key findings in each of these areas are listed as follows:

4.1 Overview of Measures

- Measures suggested by individual countries have been listed in their National Communications but costs and impacts of measures have not yet been determined. In addition, in the communications of the economies in transition many of the reported measures are still in the proposal stage.
- There is a major focus on the energy sector; necessity and affordability of measures in this sector are very dependent on economic development, which is particularly uncertain for economies in transition.

- Measures need to be identified that can be financed in the short term, given the financial situation of economies in transition. Financial shortages are closely linked to the low priority of environmental issues on the political agenda.
- Possibly the most important potential for emission reduction in the energy sector is demand side, rather than supply side management. However, the current over capacity of electric utilities (due to the shrinking economies) has created resistance to demand side management in the energy sector.
- There is a strong belief that there are many profitable and no-regret measures that can be identified in the economies in transition, particularly in the energy and transport sectors. The most important barrier, however, is expected to be the financing necessary investments. With environmental issues as a low political priority, even economically profitable measures will be difficult to finance.
- An important weakness in the economies in transition is the inadequacy of the institutional framework, particularly concerning enforcement of environmental regulation.
- NGOs must play an important role in identifying environmental measures, putting issues on the political agenda, raising awareness, and setting priorities.
- It is anticipated that Joint Implementation (JI) could have a positive impact on economies in transition. JI simulation studies show that there are potential benefits for host countries but these need to be carefully monitored. JI can also contribute to the creditworthiness of local organisations looking for investment financing.

4.2 Modelling Impacts

- The modelling frameworks that are being developed in countries of Central and Eastern Europe are seen as a major step forward to identify cost-effective emission reduction strategies.
- Macro-Economic Reference Scenarios should be developed in co-operation with decision makers from different government ministries and other agencies to raise the acceptability and credibility of the modelling results.
- In addition to cost-effectiveness of strategies (overall economic impacts), other evaluation criteria for emission reduction strategies must be considered, including: distribution of costs of emission reduction over stakeholder groups, contribution of different sectors to emission reduction, financial feasibility, social acceptability, and political/institutional feasibility.
- In order to develop an acceptable emission reduction strategy government, private sector and NGO representatives must be actively involved in the strategy development and analysis process.

- Modelling efforts within economies in transition are complicated by uncertainty as to whether adopted measures will actually be implemented.

4.3 Negotiating Action Programs

- International cooperation raises the acceptability of taking action nationally.
- To date, climate change response policy measures have focused on profitable and no-regret measures.
- Government agencies can more successfully negotiate voluntary agreements with sectoral representatives because industries prefer the flexibility of voluntary agreements over regulation-based approaches.
- Government, inter-agency cooperation is a necessary condition to achieve successful emission reduction strategies. The role of the environment ministry can only be strong if backed by public support and a clear government mandate. Thus, the main responsibility for development of emission reduction strategies must fall to the sectoral ministries, with a co-ordinating role for the environment ministry.
- NGO-based energy-efficiency, awareness campaigns can be organised at a fraction of the cost of official government campaigns. A focus on the voluntary nature of such programs actually increases their effectiveness.

Acknowledgments—The authors acknowledge the input of all workshop participants, but particularly the contributions of the various working group co-chairs and rapporteurs namely: *Craig Ebert, Tibor Faragó, Ervin Gossen, Bo Lim, Csaba Nemes, Frank Rijsberman* and *Anatoly Schuidenko*.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Carbon Dioxide Emissions from Fossil Fuel Burning: Emissions Coefficients and the Global Contribution of Eastern European Countries

[1]**Gregg Marland, Tom Boden**[1], and **Robert J. Andres**[2]

[1]*Oak Ridge National Laboratory, Oak Ridge, TN 37831-6335, USA*

[2]*University of Alaska Fairbanks, AK 99775-5900, USA*

Abstract—This paper addresses two areas of interest in the preparation of country estimates of carbon dioxide (CO_2) emissions: the accuracy and appropriateness of emissions coefficients and the global context of national emissions from Eastern Europe. Emissions of CO_2 from fossil-fuel consumption are calculated as the product of an activity factor (the amount of fuel consumed) and an emissions coefficient (the quantity of CO_2 discharged per unit of fuel consumed). Using data for 1063 coals, 6743 samples of natural gas, and nearly 200 crude oils, we show that properly defined emissions coefficients should be appropriate over a large range of fuels. The *IPCC/OECD* (1995), for example, defines emissions coefficients in units of kg CO_2 per 10^9 J that should be accurate within 2 or 3% for most fuels. International statistics on fuel consumption can be no better than the data collected and reported from individual countries and the best estimates of a country's CO_2 emissions will be calculated by those with the best access to and understanding of national fuel statistics. We use international fuel statistics to provide estimates of CO_2 emissions from all countries and to get a perspective of national and regional emissions in the global context. In 1992, global emissions of CO_2 from fossil fuels (and manufacture of cement) were about 6.10×10^9 tons of carbon (C) (1 ton = 10^3 kg). Of this, 1.15×10^9 tons C (18.8%) were from the countries we characterize here as Eastern Europe. This fraction was as high as 24.4% of the global total in 1985 and is continuing to decrease.

Key-words: carbon dioxide, Eastern Europe, emissions coefficient.

1. Introduction

For most countries, the emission of CO_2 from energy systems is the most important contribution to global emissions of greenhouse gases. This paper addresses two areas of interest in the preparation of estimates of CO_2 emissions from the energy systems of individual Eastern European countries: the accuracy and appropriateness of emissions coefficients, and the global context of emissions from Eastern Europe.

2. Emissions Coefficients

Because it is impractical to measure all emissions to the atmosphere, we seek to devise calculation procedures that provide a reasonable estimate of emissions. Emissions of CO_2 from fossil-fuel consumption are generally estimated as the product of an activity factor (the amount of fuel consumed) and an emissions coefficient (the quantity of CO_2 discharged per unit of fuel consumed). The IPCC/OECD methodology (*IPCC/OECD*, 1995), now being used by most countries for estimating greenhouse gas emissions, offers emissions coefficients for the various fuels with acknowledgment that the coefficient for bituminous coal, for example, is an estimate for an average bituminous coal and that the correct value will be different for each bituminous coal. The same is true for other fuels. Countries are encouraged to use analytical data based on their own fuels when the data are available, and the IPCC/OECD methodology remains a 'live' document in that it is subject to revision if improvements are suggested after an initial period of application.

Accurate estimation of emissions involves the selection of appropriate measures of activity and compatible emissions coefficients. In addition, we would prefer emissions coefficients that are applicable, or easily adaptable, over a wide range of countries and circumstances as this reduces the data-intensiveness of the estimation process and facilitates the comparison and verification of estimates from different scientists. It is especially likely that we can derive simple emissions coefficients for CO_2 because CO_2 is the equilibrium product of fossil-fuel combustion and we have only to worry about the chemistry of the fuel and the efficiency of combustion. Some carbon (C) is discharged as carbon monoxide (CO) or unburned hydrocarbons but, if our interest is in CO_2, these compounds are soon converted to CO_2 (although methane has a mean lifetime on the order of 10 years) and there is little loss in assuming instantaneous conversion. For incomplete combustion we need only to worry about the carbon that is spilled, retained unoxidized in the ash, or is discharged as soot (black carbon); and the latter two generally sum to less than 1% in large, and most small, combustion systems (see, for example, *Marland* and *Rotty*, 1984).

Coal is a variable commodity and we know that the mass fraction of carbon in coal varies widely. As a result, for solid fuels, the IPCC/OECD suggests emissions coefficients with the denominator expressed in energy rather than mass units. The underlying presumption is that there is a correlation between the energy content and the carbon content of coal. This emissions coefficient is based on the lower heating value (net heating value – NHV) of the fuel, i.e. the heating value is measured at constant pressure and the combustion-product water is in the vapor phase. The activity value — quantity of coal consumed — must also be in terms of the lower heating value of the coal. To see how well the emission of C from coal combustion is represented by a one-parameter relationship between carbon content and heating value, we plotted (*Fig. 1*) carbon content vs. heating value (dry basis) for 1063 U.S. coals (*Pennsylvania State University*, 1993) and solved the linear regressions for 3 different coal ranks. If the best-fit line passes through the origin ($y = mx + b$ and $b = 0$), the slope will be the simple coefficient which is sought. In fact the best fit linear regression lines do not pass through the origin (the heating value of coal depends on the carbon content but also on the content of hydrogen, oxygen, and sulfur and the heat capacity of the incombustible fraction) but the quality of the fits is only slightly affected if we constrain the lines to pass through the origin (*Marland et al.*, 1994a). The data set is sufficiently large that we can distinguish among three ranks of coal and calculate standard errors for the carbon estimates. The coefficients are summarized in *Table 1*. As seen in Table 1, the standard errors of the carbon estimates are slightly over 2% when expressed in terms of CO_2 emissions.

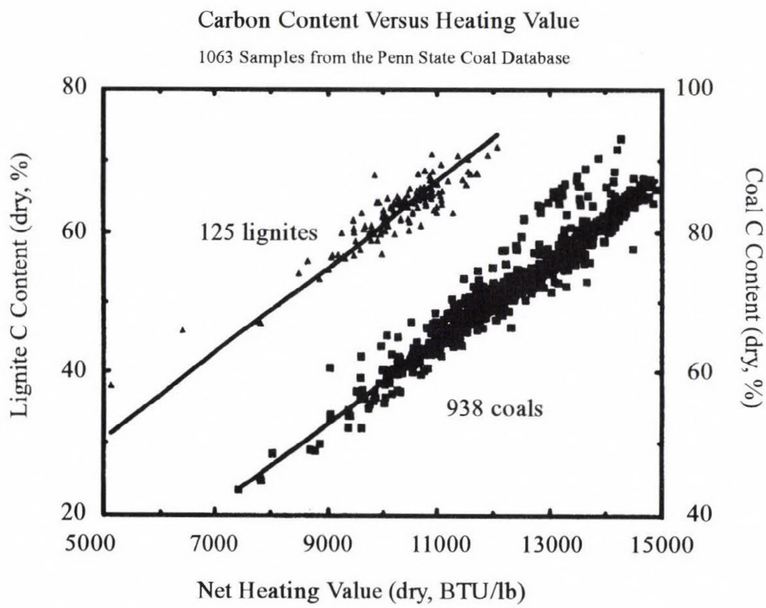


Fig. 1. The carbon content of coals plotted against the lower (or net) heating value (NHV). Data for lignites are set off by 20% (see left-hand axis) from the data for hard coals (see right-hand axis) in order to make the data more distinguishable. The lignites include brown coals. Data for anthracite coals are included with the hard coals and show primarily as a band of points just above the main data cluster. Heating value is plotted in the original units of BTU/lb where 1 BTU/lb = 2324 J/kg (from *Marland et al.*, 1994a).

Table 1. Emissions coefficients for CO_2 from solid fuels [kg $C/10^9$ J (NHV[#])]

Fuel	IPCC/OECD	This analysis	Standard error of carbon estimate (%C)
Anthracite	26.8	27.27	2.57
Coking coal	25.8		
Other bituminous	25.8	26.16	2.09
Sub-bituminous	26.2		
Lignite	27.6	26.22*	2.33*
Peat	28.9		

[#] = net heating value
* = lignite and brown coal

Winschel (1990) has also plotted data for a large number of coals and likewise found a relationship between heating value and carbon content. *Hong* and *Slatick* (1994) examined data on 5426 coals to determine if there were significant differences in the coefficients as a function of the year of analysis (an indication of changing laboratory technique) or whether or not the coal had been washed. These factors did little to explain the variability in the data and were judged to be not important. *Hong* and *Slatick* (1994) did find some areal variation even when they limited comparison to a single coal rank; the emissions coefficients varied over a range of 4.9% when averages from 27 U.S. states were compared.

Our conclusion is that for coals (excepting the unlikely possibility that this large and varied sample of U.S. coals is a poor representative of world coals), a single emissions coefficient based on the heating value of coals does indeed enable accurate estimation of CO_2 emissions, with errors less than 2.5% for most coals. Adjustment should be made in applications where the unoxidized fraction is known to be high. Our best estimate of the emissions coefficient for bituminous coal is only 2.5% less than that suggested by the IPCC/OECD (see Table 1) and 0.2% greater than the value *Hong* and *Slatick* (1994) suggest for the U.S. average (when adjusted to common units).

Natural gas that is marketed for energy use is less variable than is coal and is sufficiently simple chemically that we can calculate emissions coefficients from the chemical analyses for individual gases. Early work by *Marland* and *Rotty* (1984) showed that the CO_2 emissions coefficient varied slightly as a function of the heating value of the gas. To arrive at an average value for the emissions coefficient, they found the mean heating value of gas that was being produced and used the emissions coefficient for that gas to apply for all gases. This carries the implicit acknowledgment that the emissions coefficient is increasingly inappropriate as the heating value of the gas deviates from the global mean, but Marland and Rotty argued that the dependence on heating value is low so that the error is generally small. Marland and Rotty used a production-weighted mean based on both the chemistry of gases and the amount of the respective gases produced, and from these derived a value of 13.70 kg C/10^9 J (GHV) for global average natural gas (based on the gross or higher heating value of the gas). Using the same logic, *Marland* and *Pippin* (1990) used 13.78 kg C/10^9 J (GHV) for U.S. average natural gas. These coefficients include an average of 0.78% CO_2 which is contained in the gas when produced but often released during processing. The *IPCC/OECD* (1995) suggests an emissions coefficient of 15.3 kg C/10^9 J (NHV) which is equivalent to 13.9 kg C/10^9 J (GHV) if we assume, as they suggest, that the gross heating value is 10% more than the net heating value (1.1 × NHV = GHV). The equation derived by *Marland* and *Rotty* (1984) to express the relationship between the emissions coefficient and heating value of natural gas is:

$$EC = 13.708 + 0.0828 \times 10^{-1} (GHV - 37.234),$$

where *EC* is the emissions coefficient in kg C/10^9 J, and *GHV* is the gross heating value in kJ/m^3.

In the process of preparing recent estimates of CO_2 emissions in the U.S., the *U.S. DOE* (1994) obtained from the Gas Research Institute data on 6743 gases marketed in the U.S. They point out that the CO_2 emissions coefficient reaches a minimum near the value for methane. Pure methane has a gross heating value of 37,420 kJ/m^3 and an emissions coefficient of 13.62 kg C/10^9 J (GHV). Because of its high H/C ratio, methane has the lowest CO_2 emissions coefficient among the gaseous hydrocarbons. There is a tendency for the emissions coefficient to increase, as noted above, for gases with an increasing content of heavier hydrocarbons, a lower H/C ratio, and higher heating value. Some gases will have lower heating values because of increasing content of inert components and the emissions coefficient will increase to the extent that this inert component includes increasing CO_2. With this insight, the relationship between emissions coefficient and heating value derived by Marland and Rotty will not be appropriate for gases with heating value much below that of pure methane.

Fig. 2 shows the *U.S. DOE* (1994) plot of CO_2 emissions coefficients vs. heating value with the suggested best fit line from *Marland* and *Rotty* (1984) superimposed. Although analysis of this DOE data set is continuing, it is clear that (1) the relationship described by Marland and Rotty is reasonably supported by this data set, (2) the emissions coefficients suggested by the *IPCC/OECD* (1995) should be within 2 to 3% of the correct value for a wide range of gases, (3) slightly higher emissions coefficients may be called for in places where separation of heavier hydrocarbons as gas liquids is less efficient, and (4) additional data may be required when dealing with gases of very low heating value. When the *U.S. DOE* (1994) calculated a production-weighted mean for U.S. natural gas, the emissions coefficient is 13.72 kg C/10^9 J. A small amount should be added to recognize that the original gas contained CO_2 that was released during processing.

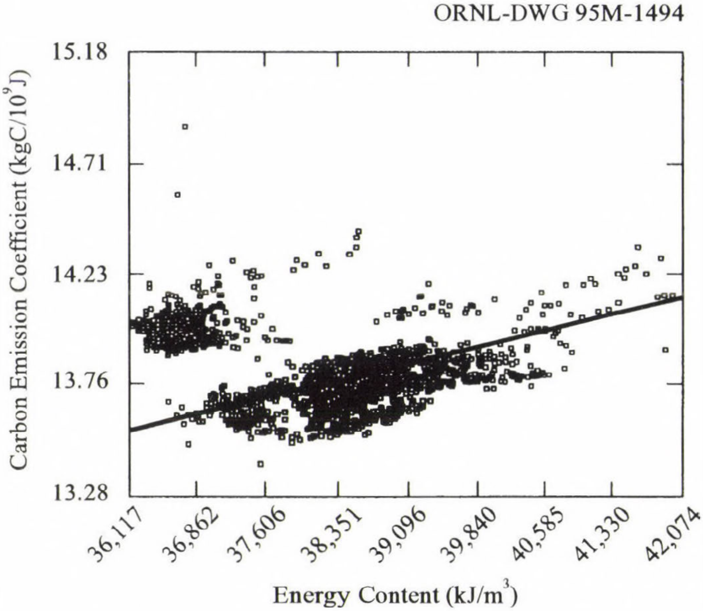


Fig. 2. Emissions coefficients calculated for 6,743 natural gas samples from the Gas Research Institute database are plotted as a function of the gross heating value of the gas (GHV). Superimposed is a line describing the relationship derived by *Marland* and *Rotty* (1984). The Marland and Rotty curve includes addition of an estimate of the amount of CO_2 released from the gas during processing.

A similar analysis of emissions coefficients for liquid fuels is also underway. An examination of crude oils is of particular interest. We should be able to describe a mass balance between the carbon content of crude oils and the carbon content of the suite of secondary petroleum products derived from it and this will provide a useful constraint on the completeness of the accounting. Data on the carbon content and heating value of crude oil and secondary petroleum products are not routinely collected and the analysis is handicapped by a shortage of data. Preliminary analyses, based on data from 191 crude oils, show that the mass fraction of carbon in crude oils varies within relatively narrow limits but does vary slightly with the density of the crude. The heating value decreases with increasing density. High density crudes tend toward an increase in nitrogen, oxygen, sulfur, and heavy metals while low density crudes have higher H/C ratios. Initial results suggest that C content is highest for crudes with specific gravity around 0.90 and that emissions coefficients increase with density. We suggest that emissions coefficients for liquid fuels may be most accurate when expressed in mass rather than energy terms, contrary to the conclusion reached for solid and gaseous fuels.

3. CO_2 Emissions from Eastern Europe

Emissions of CO_2 from the energy systems of Eastern European countries can be estimated using data available in international data sets or using data available from domestic data sources. In theory these two approaches should yield the same result because the international data compilations of the *United Nations* (1994) and the *International Energy Agency* (1991), for example, are based largely on data collected and reported by individual countries. Our expectation is that estimates computed by national sources will, in fact, differ slightly because of differences in the completeness of data collection and reporting, differences in the richness of the data sets available, differences in understanding of the details and nuances of the data, differences in the manner in which the data are aggregated, perhaps differences in details like the categories used or the reporting periods. The international data have one advantage in that a significant effort has been invested in trying to ensure that the data are presented in a standard way for all countries and that comparisons can be easily made. Where CO_2 emissions estimates based on international data sources differ by more than a few percent from those based on national data sources, we should be able to learn from those differences something about the completeness and quality of the data available or of the individual characteristics of national energy systems.

To provide first estimates of CO_2 emissions from Eastern Europe and to provide perspective on the magnitude of these emissions in a global context, we have used data from the United Nations Statistics Office to estimate emissions from each country and from the world as a whole. Data presented here include emissions from calcining limestone during cement manufacture, based on cement production data from the U.S. Bureau of Mines (*Solomon*, 1994). Our estimation procedures differ slightly from those embodied in the IPCC/OECD methodology and the details and coefficients are described in *Marland* and *Rotty* (1984). One important difference should be noted. Because we have a procedure used uniformly for every country, and because the use and fate of non-fuel petroleum products differ significantly among countries, our national totals for emissions from petroleum are based on energy uses only and do not include emissions from the oxidation of non-fuel products. National estimates that include oxidation of non-fuel liquid petroleum products should run slightly higher than our values. As in the IPCC/OECD methodology, our national totals do not include emissions from biomass fuels or from international bunker fuels.

On the other hand, our global total does include emissions from international bunker fuels and the oxidation of non-fuel petroleum products. Note that the U.N. reports no venting or flaring of natural gas in the USSR and the numbers shown here were derived from other sources, largely the U.S. Department of Energy (*U.S. DOE*, 1995).

Data on the global total of emissions and the regional distribution thereof are found in *Marland et al.* (1994a and 1994b). The global total of CO_2 emissions from fossil fuels and cement production reached 6.10×10^9 tons C in 1992 (1 ton = 10^3 kg).

Fig. 3 shows the total of CO_2 emissions to the atmosphere from Eastern Europe and the former USSR. With the political and economic changes taking place in the region it is not obvious how the region should be defined and yet there is utility in maintaining a regional perspective of recent history. Our graphs for Eastern Europe do not include the former German Democratic Republic. Eastern Europe, as used here, includes all of the former USSR, Albania, Bulgaria, Czech Republic, Hungary, Poland, Romania, and Slovakia. *Fig. 4* shows CO_2 emissions from Eastern Europe as a fraction of the global total. Eastern Europe is seen to contribute some 20% of global total CO_2 emissions, a fraction that has been declining with the recent economic restructuring but that has the potential to resume the growth which preceded the late 1980s. Per capita emissions of CO_2 from Eastern Europe in 1992 were 3.0 tons C per year, compared with an average of 2.2 tons C per year in Western Europe and a global average value of 1.1 tons C per year.

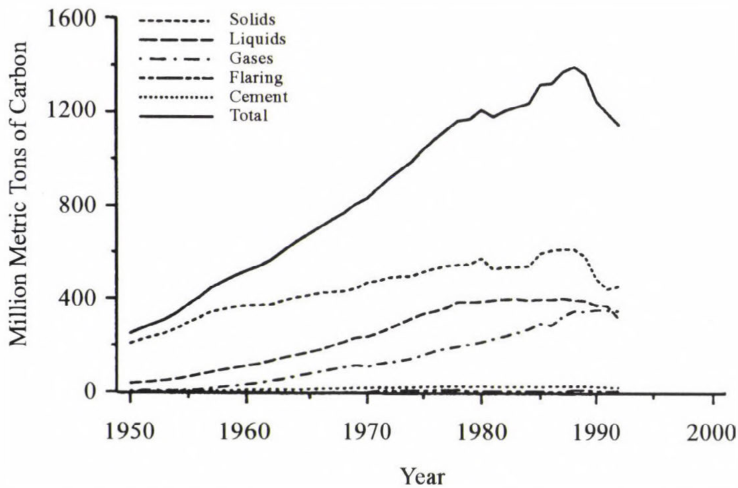


Fig. 3. CO_2 emissions from fossil-fuel consumption and cement manufacture in Eastern Europe. As shown here, Eastern Europe includes all of the former USSR but does not include the former German Democratic Republic.

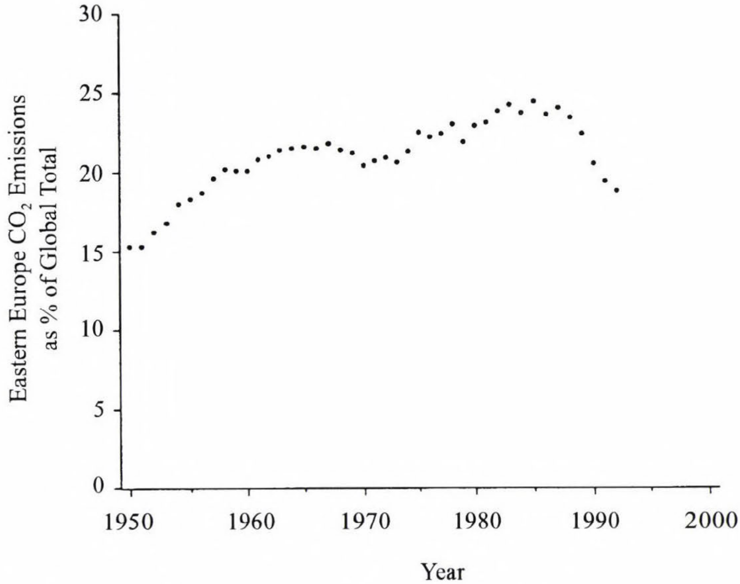


Fig. 4. CO_2 emissions from Eastern Europe as a fraction of the global total of emissions from fossil-fuel consumption and cement manufacture. Emissions from the oxidation of non-fuel petroleum liquids (such as lubricants and petrochemical feedstocks) and from international bunker fuels are included in the global total but not in the Eastern European total.

As in other regions, emissions from Eastern Europe are dominated by a small number of the larger countries. In fact, a list of the 20 countries with largest contributions to global total CO_2 emissions includes 4 Eastern European countries: Russia, Ukraine, Poland, and Kazakhstan (see *Fig. 5*). The historic time series of CO_2 emissions from all Eastern European countries are included in the Appendix. With the break-up of the USSR, that time series of emissions terminates in 1991 and we have data to estimate emissions from each of the individual countries. Estimates for 1992 are shown in *Table 2*.

A few estimates of national CO_2 emissions from Eastern Europe based on national data provide for comparison with the values presented here. *Lévai and Mészáros* (1989) reported a value for CO_2 emissions from Hungary in 1987 which is 16% higher than the value reported here. Estimates for Hungary, Poland, and Czechoslovakia in 1988 were reported by *Klimont et al.* (1994) and are 18%, 3%, and 8%, respectively, larger than the values reported here. All of these values appear to include oxidation of non-fuel petroleum products and are, as expected, slightly higher than our estimates. The estimates for Hungary differ sufficiently to suggest a problem somewhere in the data.

To emphasize the burdens on international data and the improvements which might occur when individual countries are more invested in the process of data collection and reporting, it is interesting to look at emissions estimates from

Albania. We estimated CO_2 emissions from Albania using data that were available from the United Nations Statistics Office in 1989 and again using data that were available in 1994 and early 1995. The two plots are superimposed in *Fig. 6*. Although the two estimates of CO_2 emissions are of comparable magnitude and the two time series retain much in common, it is clear that the more recent data not only extend the time series but represent significant revision of earlier energy data. Presumably these revisions represent additional data reported to the U.N. or otherwise made available to the international community. The prominent emissions peak which once appeared in 1975 has disappeared but a prominent valley now appears in 1980. Someone familiar with the energy situation in Albania should be able to judge if these features in the graph represent real events in the Albanian economy or if they are defects in the data series.

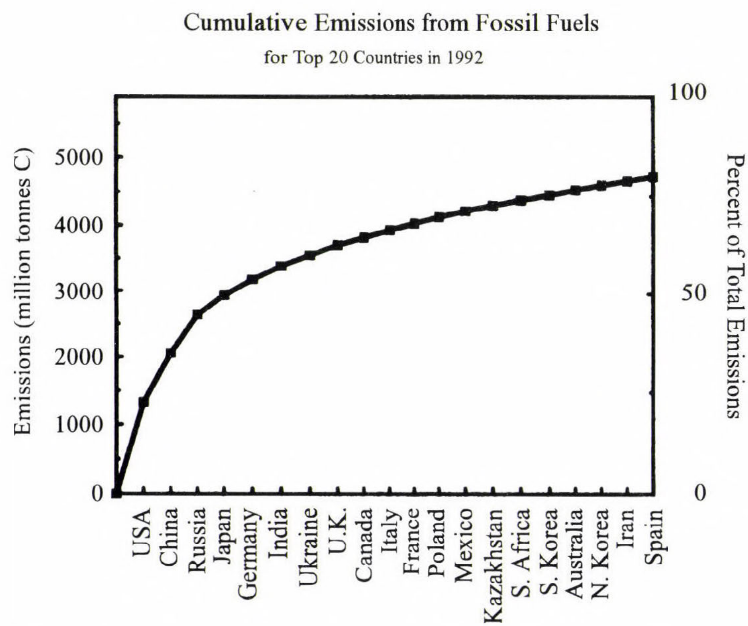


Fig. 5. The cumulative sum of emissions of CO_2 from fossil-fuel consumption and cement manufacture in 1992. The 20 countries with the largest emissions are shown in order of decreasing annual emissions. The cumulative sum is shown (right-hand axis) as the fraction of the sum of all countries. The sum of all countries is less than the global total of emissions because the country values do not include oxidation of non-fuel, liquid petroleum products or of fuels used in international commerce.

Table 2. CO_2 emissions from fossil-fuel consumption and cement manufacture in the former USSR in 1992 (10^6 tons C, where 1 ton = 10^3 kg) (0.0 means < 0.05)

Country	Solid fuels	Liquid fuels	Gas fuels	Cement	Gas flaring	Total
Russia	165.7	186.5	206.8	9.3	5.8	574.0
Ukraine	84.0	29.5	50.6	2.7	0	166.9
Kazakhstan	55.1	15.8	9.7	0.8	0	81.3
Uzbekistan	5.0	6.2	21.6	0.8	0	33.6
Belarus	2.6	16.7	8.3	0.2	0	27.8
Azerbaijan	0.0	10.8	6.1	0.1	0.5	17.4
Turkmenista	0.2	5.4	5.9	0.1	0	11.5
Lithuania	0.5	3.4	1.8	0.3	0	6.0
Estonia	4.2	1.0	0.4	0.1	0	5.7
Kyrgyzstan	1.8	1.3	1.0	0.1	0	4.2
Latvia	0.5	2.1	1.4	0.1	0	4.0
Moldavia	1.4	0.3	1.9	0.2	0	3.9
Georgia	0.5	0.6	2.5	0.1	0	3.8
Armenia	0.1	0	1.0	0.1	0	1.1
Tajikistan	0.1	0.0	0.9	0.0	0	1.1
Total	**321.7**	**279.6**	**319.9**	**15.0**	**6.3**	**942.3**

4. Conclusions

Emissions of CO_2 from energy systems are the most important anthropogenic source of greenhouse gases emission in the atmosphere. It is possible to derive appropriate emissions factors to estimate CO_2 emissions based on common measures of fuel consumption. Errors on the basis of emissions factors should be less than 2 to 3% for most fuels. National emissions estimates for Eastern Europe show that the region is an important user of fossil fuels, contributing on the order of 20% to the global total of CO_2 emissions. Both the absolute and fractional contributions have been declining during the economic restructuring of the last decade.

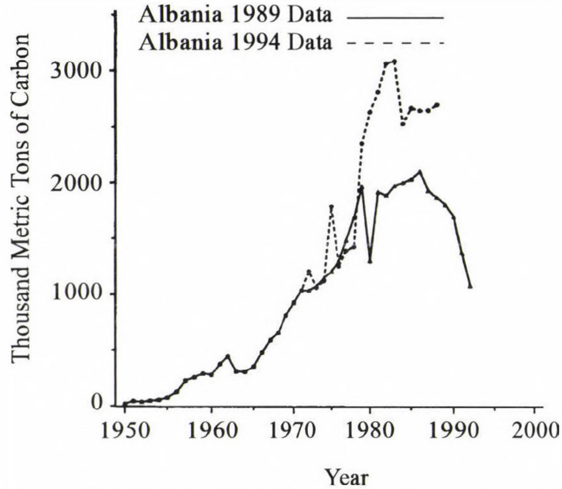


Fig. 6. Emissions of CO_2 from fossil-fuel consumption and cement manufacture in Albania have been estimated using energy statistics available from the United Nations Statistics Office in 1989 and again using data available in 1994.

References

Hong, B.D. and *Slatick, E. R.*, 1994: Carbon Dioxide Emission Factors for Coal. U.S. Department of Energy, Energy Information Administration, Quarterly Coal Report Jan-Mar, p. 1-8.

IPCC/OECD, 1995: *IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3, Greenhouse Gas Inventory Reference Manual*. United Nations Environment Programme, The Organisation for Economic Co-operation and Development, International Energy Agency, Intergovernmental Panel on Climate Change; UK Meteorological Office, Bracknell.

International Energy Agency, 1991: *Energy Balances of OECD Countries 1989-1990*. Organization for Economic Co-operation and Development, International Energy Agency, Paris.

Klimont, Z., Amann, M., Cofala, J., Gyárfás, F., Klaassen, G. and *Schopp, W.*, 1994: An emission inventory for the Central European initiative 1988. *Atmos. Environ. 28*, 235-246.

Lévai, A. and *Mészáros, E.*, 1989: Energy production and carbon dioxide emissions in Eastern Europe with special reference to Hungary. *Időjárás 93*, 196-204.

Marland, G. and *Rotty, R.M.*, 1984: Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982. *Tellus 36B*, 232-261.

Marland, G. and *Pippin, A.*, 1990: United States emissions of carbon dioxide to the earth's atmosphere by economic activity. *Energy Systems and Policy 14*, 319-336.

Marland, G., Andres, R.J. and *Boden, T.*, 1994a: Magnitude and Trends of CO_2 Emissions. In *Global Climate Change: Science, Policy, and Mitigation Strategies* (eds.: *C.V. Mathai* and *G. Stensland*. Air and Waste Management Association, Pittsburgh, PA, pp 215-226.

Marland, G., Andres, R.J. and *Boden, T.A.*, 1994b: Global, regional, and national CO_2 emissions. In *Trends 93: A Compendium of Data on Global Change* (eds.: *T.A. Boden, D.P. Kaiser, R.J. Sepanski,* and *F.W. Stoss*). ORNL/CDIAC-65, Carbon Dioxide Information Analysis Center, Oak Ridge, TN, pp. 505-584.

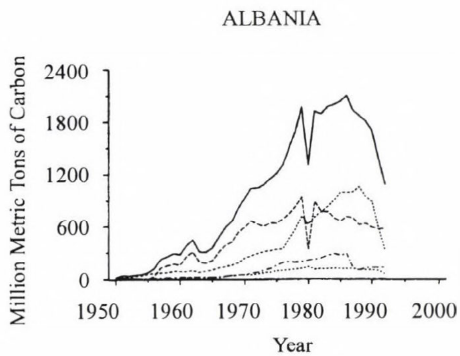
Pennsylvania State University, 1993: *Penn State Coal Data Base of the Coal and Organic Petrology Laboratories*. Pennsylvania State University, State College, PA.

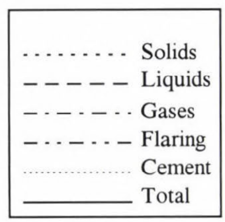
Solomon, C., 1994 (and earlier reports in the same series): *Cement Annual Report*. U.S. Department of the Interior, Bureau of Mines.

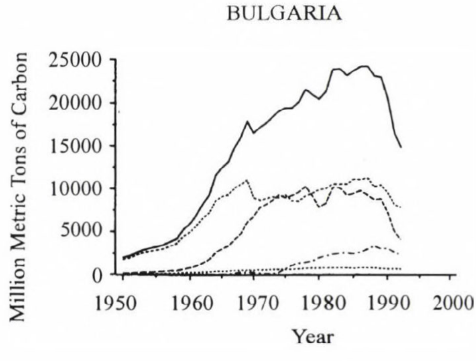
United Nations Statistical Office, 1994 (and earlier and electronic versions of the same series): *1992 Energy Statistics Yearbook*. The United Nations Statistical Division, New York.
United States Department of Energy, Energy Information Administration, 1994: *Emissions of Greenhouse Gases in the United States 1987-1992*. U.S. Government Printing Office, Washington, D.C.
United States Department of Energy, Energy Information Administration, 1995: *International Energy Annual 1993* (and earlier reports in the same series). DOE/EIA-0219(93), U.S. Government Printing Office, Washington, D. C.
Winschel, R. A., 1990: The relationship of carbon dioxide emissions with coal rank and sulfur content. *J. of the Air and Waste Management Association 40*, 861-865.

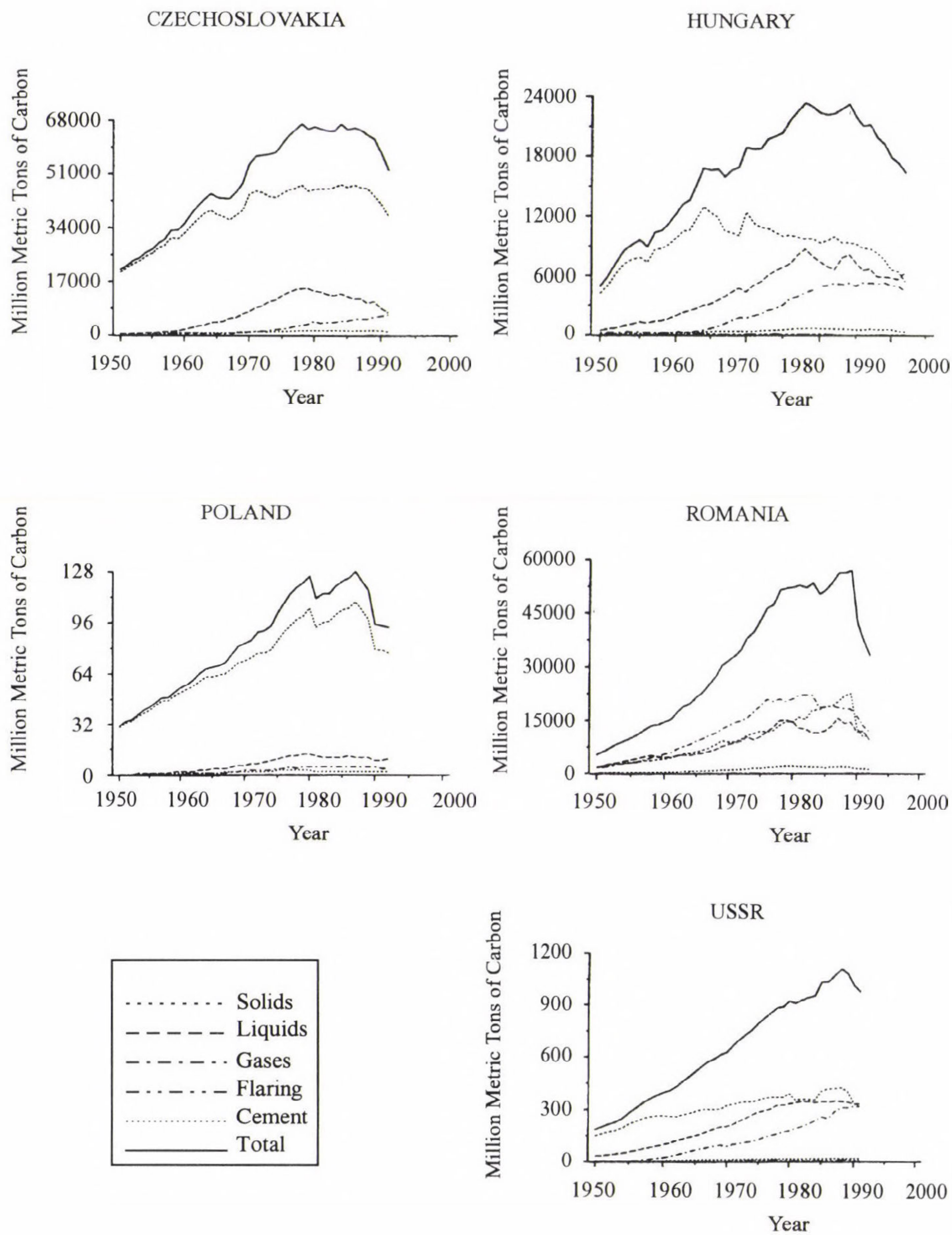
APPENDIX

Emissions of CO_2 from fossil-fuel consumption and cement manufacture in the countries of Eastern Europe. The time series for the former USSR ends in 1991 and data for the individual countries for 1992 are summarized in Table 2 above. The time series for Czechoslovakia also ends in 1991. For 1992, emissions from the Czech Republic are estimated at 37011 $\times$ 10^3 tons C and those from Slovakia at 10098 $\times$ 10^3 tons C, for a total of 47019 $\times 10^3$ tons C (down from 52226 $\times$ 10^3 tons C in 1991).








CZECHOSLOVAKIA
HUNGARY
POLAND
ROMANIA
USSR
Million Metric Tons of Carbon
Year
68000
51000
34000
17000
24000
18000
12000
6000
128
96
64
32
60000
45000
30000
15000
1200
900
600
300
0
1950
1960
1970
1980
1990
2000
Solids
Liquids
Gases
Flaring
Cement
Total

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

The IPCC Inventory Methods and their Application and Limitations in Eastern Europe: Energy, Industrial Processes, and Wastes

Craig Ebert[1] and **Milos Tichy**[2]

[1]*ICF Incorporated, 1850 K Street, N.W. Suite 1000, Washington, D.C. 20006, USA*

[2]*SEVEN, Slezska 7, CZ-12056, Praha 2, Czech Republic*

Abstract—Countries throughout Central and Eastern Europe have used the IPCC Inventory Guidelines for developing national greenhouse gas emission estimates for energy, industrial process, and waste categories. In applying the IPCC methodologies, several challenges have been encountered. The greatest problem has been development of accurate CO_2 emission estimates from energy, due to difficulties in obtaining reliable energy data at the national and sectoral level. Many of these challenges relate directly to the rapid rates of economic and political change experienced in recent years. Nevertheless, these countries have also been able to generate significant amounts of new information for the IPCC Inventory Program, including emission factors for gases other than CO_2 more representative of combustion processes in the region, country-specific estimates of the rate of methane leakage from coal mining, and industrial processes not currently included in the IPCC Guidelines.

Key-words: greenhouse gas emissions, CO_2 emissions, energy, industrial processes, wastes, IPCC inventory methods, top-down and bottom-up methodologies, Eastern Europe.

1. Introduction

The IPCC emission inventory methods provided the starting point for Eastern European countries as they compiled their national GHG emissions inventories. In several instances, however, the IPCC inventory methods were refined as countries discovered more information for improving the description of emission pathways reflected in the methods. In this paper the basic reactions to the inventory methods for the energy sector and industrial processes are reviewed, along with some of the major challenges associated with estimating emissions from these source categories. The intention is to highlight those issues of greatest relevance to Eastern European countries as they have attempted to improve the accuracy of emission estimates in their countries.

The first section of this paper comments on emissions from energy consumption, beginning with CO_2 from energy then emissions from bioenergy and emissions other than CO_2 from energy. The second section discusses the methodologies for estimating emissions from energy production activities, particularly methane releases during coal mining activities and methane releases during the production of oil and natural gas. The third section reviews industrial processes, and also briefly addresses emissions from solvents and waste processes.

2. Emissions of CO_2 from the Consumption of Energy

The largest emission source category for most countries in Eastern Europe is CO_2 from the consumption of fossil fuels. The challenges faced by countries estimating these emissions are discussed below, then key issues related to other energy combustion source categories are presented.

2.1 Top-Down Versus Bottom-Up Methodologies

The IPCC Reference Approach for estimating emissions of CO_2 from the combustion of fossil fuels is a 'top-down' methodology since it is based on aggregate, national energy statistics that reflect the production of carbon within a country and the flow of carbon into and out of it. The IPCC believes that this method is the most accurate for most countries for determining emissions of CO_2 because it comes closer than any other method for ensuring that all energy consumed in the country is captured in the methodology. This is because countries often collect fairly reliable energy data at the national level, but may not be able to identify all consumers of energy.

The major limitation of the Top-Down method, however, is that it does not provide the type of detailed, disaggregated emission estimates that are often required for analyses conducted by Eastern European countries, such as mitigation studies. For example, the Reference Approach will not readily provide emission estimates by sector of the economy, region within a country, or technology type. As a result, countries are also encouraged to include estimates from a 'Bottom-Up' methodology, which is based on detailed estimates of consumption at various levels of disaggregation (e.g., by sector of the economy). To this point, however, only a few Eastern European countries have attempted to estimate CO_2 emissions from energy using the 'bottom-up' approach.

While, in theory, the top-down and bottom-up approaches should yield the same results, in practice we have found that discrepancies may exist for several reasons. Discrepancies between the top-down and bottom-up assessments have been divided into two main categories: (1) those discrepancies that affect the determination of the amount of energy consumed; and (2) those that affect the estimates of the amount of carbon emitted from the energy consumed.

2.2 Discrepancies Affecting Estimates of Energy Consumption

Most discrepancies in Eastern European countries between the top-down and bottom-up methodologies can be traced to inconsistencies in the energy data. Specific areas identified include differences in:

(1) Product definitions;

(2) Heat equivalents;

(3) Data sources (consumer surveys, producer surveys, sales reports, etc.); and

(4) Accounting procedures.

Product Definitions: The fuel categories used for the top-down approach are sometimes different than those in the bottom-up approach. This requires verification that the same fuels are accurately reported in both inventories. Some examples are as follows:

(1) Crude oil is not typically consumed directly in most countries, but is refined into other products. The bottom-up assessment reports consumption of these refined products directly, so it is necessary to insure that all petroleum derivatives are included.

(2) Due to the way energy data are collected, bottom-up calculations may report sector-specific energy statistics (e.g., coal use disaggregated by residential, commercial, industrial coking, industrial other, and transportation), while the top-down method uses aggregate categories (such as coking coal and steam coal).

(3) Products used in one method may be a combination of products used in the other method. For example, LPG in the bottom-up calculations may be actually a combination of the NGL and LPG statistics used in the top-down methodology.

(4) Some categories may be unique from one methodology to the next. For example, bottom-up categories such as special naphthas, miscellaneous petroleum products, and gasoline blending components may not correlate directly to categories contained in the top-down assessment.

Heat Equivalents: It can be difficult to obtain heat equivalents for certain fuel types, which could introduce differences in the final emissions estimates depending on the inventory method used.

Data Sources: Since the basic data structure of the two methods is different, the procedures for collecting data are often different. The bottom-up method uses actual reported consumption while the top-down method uses apparent consumption derived from national energy flows. Countries often place different emphasis on collecting one type of date versus another.

Also, discrepancies may exist due to the actual data collection techniques. Some typical methods of data collection used in both bottom-up and top-down inventories are regulatory reporting, end user surveys, production and sales reports, customs records, and expert estimation. Each type of collection method may leave certain gaps in data. For example, surveys may not reach all possible users. Since top-down and bottom-up inventories obtain their data differently, it is not surprising that the gaps found in one may not be present in the other, and vice versa.

Accounting Procedures: Since the basic structure of the data is different, bottom-up methodologies and top-down methodologies may not account for fuel in the same way. Two particular areas of concern are international bunker fuels and accounting for energy used as geographic boundaries have changed (e.g., due to the breakup of the Soviet Union or Czechoslovakia).

2.3 Discrepancies Affecting Estimates of Carbon Emissions

Carbon Coefficients: Carbon content coefficients may be more accurate for a country using one method as opposed to another. For example, the top-down methodology often relies on default carbon coefficients provided by the IPCC (IPCC/OECD, 1994; Vol. 2), while the bottom-up methodology uses country-specific coefficients believed to more accurately reflect national circumstances. For instance, the top-down methodology uses a globally averaged carbon coefficient for crude oil (which captures the bulk of any country's oil consumption), while the bottom-up methodology uses technology specific carbon emission coefficients that allow countries to estimate emissions with greater precision.

Product Definitions: Just as it can be difficult to obtain an accurate estimate of the heat content of certain products, it can also be difficult to define accurately the carbon content for such products as uncertainties in overall fuel quality carry over into uncertainties in carbon content.

3. Emissions Other than CO_2 from Energy Combustion

Countries throughout Eastern Europe are extremely interested in developing reliable estimates of gases other than CO_2, i.e., CH_4, NO_x, CO, and NMVOCs, from energy consumption. In most instances there are on-going programs in place to develop estimates for at least some of these gases. As part of this objective, many countries feel it is very important to harmonize the development of emissions with other regional and national inventory programs such as CORINAIR, REZZO (Czech Republic), among others. For example, the Czech

Republic compared estimates using both the IPCC and CORINAIR methodologies, and in some cases, found significant differences. These differences were believed to stem mainly from differences in source categorization and default emission coefficients.

Several country inventory teams have also noted that the default factors provided by the IPCC for energy combustion (both stationary and mobile sources) depend heavily on experiences in the U.S. and Western European countries. Emission factors reflecting combustion conditions in Eastern European countries need to be included in the IPCC methods. Many countries have included official national estimates of some gases, such as CO, N_2O, and NO_x, in their inventories. These emission estimates have been collected as part of on-going requirements to report such information, and represent a wealth of information on combustion processes throughout Eastern Europe. Strong efforts must be made to consolidate this information for easy access by many countries, develop new data in some areas that reflect regional conditions, and coordinate the development of consistent methodologies among different programs.

4. Emissions from the Production of Energy

Eastern Europe has two major source categories from the production of energy: (1) methane releases during coal mining; and (2) methane releases from oil and gas production activities.

4.1 Emissions from Coal Mining

The IPCC methodologies for estimating methane releases from coal mining are based on the estimated quantity of methane contained in the coal seam being mined and any additional methane that may be released from the surrounding strata. Some Eastern European countries have found that sufficient information exists within their own countries to refine the emission factors. These revised factors have been based on conversations with coal industry experts in the country, who are often aware of the extent of methane in the coal seams based on engineering studies done for existing mines and experiences gained in operating existing mines. As a result, countries have been able to develop country-specific emission factors, or at least identify whether coal basins in the country are higher or lower emitters of methane. This information should be incorporated into the IPCC methods and disseminated to countries throughout Eastern Europe to assist the entire region with the estimation of these emissions.

4.2 Emissions from Oil and Gas Production Activities

During most phases of oil and gas production activities gases can be released, particularly methane. The IPCC methodologies have subdivided these activities into several categories to account for the range of emission conditions. The main subcategories have been broadly defined as crude oil and natural gas production; crude oil transportation and refining; and natural gas processing, transport, and distribution. Estimating emissions from these activities is very complex due to the wide variety of conditions found throughout the world. In many cases the oil and gas systems in Eastern Europe are unique in terms of the equipment used, the configuration of the industry, operation and maintenance procedures, among other factors. The IPCC Guidelines describe only a limited amount of information for developing acceptable emission factors. We have found that additional information exists from Eastern European countries, such as Russia and Poland, that allows countries to significantly improve the quality of their emission estimates. This information should be incorporated into the IPCC methodologies and disseminated to countries throughout the region. Secondarily, countries should also be encouraged to contact their national industry experts to discuss conditions in their country to determine the magnitude of releases. These discussions should focus on the entire cycle of emissions from initial production of oil and gas within the country to distribution of the products to the consumer. The industry experts are often aware of the specific practices in the country that can lead to emissions and are often familiar with the approximate extent of gas that may be lost during the various parts of the production cycle.

5. Other Observations

Based on progress on emission inventories to date among Eastern European countries, several additional observations are offered below.

(1) Some Eastern European countries have relied heavily on the MINERGG software developed by the OECD to estimate emissions of CO_2 from energy and other source categories. Use of the MINERGG software, however, conceals all intermediate calculations and therefore, makes it hard to evaluate a country's inventory. If countries rely on MINERGG for estimating emissions, it is still important to provide detailed written documentation of the inventory calculations, particularly if country-specific assumptions have been used instead of the default factors and coefficients provided.

(2) In the inventory work performed to date in Eastern Europe, countries have suggested country- and regional-specific estimates of emissions factors that should be communicated to the IPCC inventory program and countries throughout Eastern Europe. Some of the areas in which this has occurred include:

- Mobile sources — Bulgaria, Kazakhstan, Russia;
- Oil shale — Estonia;
- Industrial processes — Kazakhstan (carbide), Czech Republic (several iron and steel processes, ammonia);
- Fuel combustion — Kazakhstan (carbon content of local fuels).

(3) Little attention has generally been paid to emissions from waste management and solvent use. The reasons for this are not clear, although possibilities include: little data availability; lack of experts in this area; and the perception that these source categories are not likely to be major emitters.

(4) More work needs to go into identifying the underlying uncertainties in emission estimates. The current IPCC guidelines provide a subjective framework for discussing uncertainty, but significantly more work is needed to quantify the uncertainty embedded in different emission calculations.

References

IPCC/OECD, 1994: Guidelines for National Greenhouse Gas Inventories.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Harmonization of Large Combustion Source Categories under the IPCC and CORINAIR Regulations

Karl Ernst Joerss

Umweltbundesamt,
Bismarckplatz 1, D-14193 Berlin, Germany

Abstract—The source categories currently used for the two emission inventory programmes differ considerably. Major differences exist in the classification of large combustion plants. This is because CORINAIR is designed as a spatial system also serving dispersion modelling purposes whereas IPCC categories originate from international energy statistics and reflect the concept of energy balances. Proposals and recommendations are made as to how to facilitate data transfer from the CORINAIR to the IPCC format and eventually arrive at fully harmonized procedures.

Key-words: emission inventory, IPCC/OECD programme, CORINAIR, greenhouse gas, source category, large-scale combustion, reconciliation.

1. Introduction

According to international agreements, national emission inventories have to be communicated to supranational bodies. Two approaches to drawing up and to presenting national inventories in a comparable form are in use: the IPCC Programme under the UN Framework Convention on Climate Change (FCCC) and the CORINAIR Programme of the European Environment Agency (EEA), which is closely linked to the European Monitoring and Evaluation Programme (EMEP) set up under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP).

The IPCC Reporting Instructions (*IPCC,* 1995), formally approved following lengthy discussions and revisions, were officially published in March 1995. On the other hand, the European Topic Center on Air Emissions is currently finalizing the CORINAIR 90 inventory (*CORINAIR,* 1993) and preparing the next run — CORINAIR 94 — to commence in 1996. There will be modifications to the regulations used so far. This process is on the way and final results are not yet available.

With regard to the establishment of emission inventories, both programmes have the same goals. Consequently, they overlap to a large extent with regard to territory covered, pollutants considered and management practice. For instance, the six major direct and indirect greenhouse gases are covered by both inventories.

Due to differences in terms of political background and timescale, however, approaches were developed virtually independent of one another. Consequently, there are substantial differences as concerns basic principles, sources included and source categories which hampers the comparability of the results and the transfer of data from one reporting scheme to the other.

Under current conditions, producers of emission inventories have to deal with two formats in parallel. The same is true for users who for political or technical reasons need an exhaustive overview. This causes extra work and can lead to misunderstandings. It need not be emphasized that such conditions prove counterproductive to the common goal of widespread recognition and use of supranational emission inventories. Therefore, it would be of great benefit if the international emission inventory community could agree on a common language in order to create data in a uniform format.

In the following, major differences between large combustion source categories will be identified and ways to overcome these obstacles proposed. The remaining differences, mainly concerning source and fuel classifications, appear less difficult to solve.

To avoid misunderstandings in this paper, 'IPCC' will refer to the 'technology-based' standard approach only. The 'IPCC Reference Approach', which only applies to CO_2, will not be addressed.

2. The Role of the Source Category Split

The process of establishing emission inventories consists of two major steps: to identify sources and to quantify their emissions. Proceeding systematically, one arrives at a source category split comprising a number of hierarchical levels structured to provide a high degree of transparency with respect to the various emission generating events.

Though conceived in principle to be directly suitable as a 'working' level for emission estimation the lowest level of the source category split may in certain cases prove to be not detailed enough depending on type of emittant and source, availability of basic data and accuracy objectives. In such cases more parameters need to be taken into account which leads to the introduction of subcategories. Important examples are road traffic and point sources, for which source-specific subsystems can be applied.

Countries that had already been drawing up inventories on a regular basis before specifically formatted reporting commitments were introduced are likely to adhere to their national practices and convert the data into the requested source categories. Such conversion procedures often require approximations and assumptions.

For reporting under official commitments or for publication purposes, one or two top-level(s) will normally be sufficient.

Due to its key function for the emission inventory process the source category split can be considered as the very backbone of the whole system.

3. Conceptual Conformities and Divergences

In *Table 1*, a broad overview is given of essential characteristics of the programmes in order to demonstrate principles and practices they have in common and what differences exist. Due to its very specific perspective an in-depth discussion of all topics would go beyond the scope of this paper.

It is important to realize that the IPCC approach has been specifically conceived for the climate change issue where no attention is paid to the exact location of greenhouse gas releases whereas the CORINAIR approach is meant to serve various purposes including modelling of atmospheric transport.

Accordingly, CORINAIR is a spatial inventory in which major emitters are presented as point sources and the remaining emissions allocated to relatively small administrative districts. These differing objectives are reflected by the principles and the definitions of the respective source categories. CORINAIR source categories have to correspond to physical sources in the sense that any specific emission generating event — occurring in physical sources — as a whole is attributed to a specific source category. By contrast, the IPCC source categories, exclusively designed as a collective approach on the national level, are not subject to such constraints.

In *Table 2*, a comparison is made between the two source category splits at the top hierarchical level: six main categories on the IPCC side versus eleven main categories (CORINAIR 90) on the CORINAIR side.

Obviously, in terms of major features, the two systems are identical. Both systems consistently differentiate between energy and non-energy induced emissions and with regard to energy between combustion and non-combustion.

As relevant compatibility problems exist for the field of energy combustion and there, in turn, only for large scale combustion — public and industrial combustion installations — the following sections focus on this problem.

In *Table 3,* the IPCC source categories are investigated in detail. With regard to emissions related to fuel combustion, the IPCC source category split directly reflects the scheme of the energy balance statistics as regularly prepared by the International Energy Agency (IEA) of the OECD.

These statistics are available for a large number of countries in a directly comparable manner and are recommended for use as an activity data base for the estimation of emissions from fuel combustion.

When discussing CORINAIR and IPCC characteristics, one has to realize that there are differences in the interpretation of important terms. The 'source

Table 1. Comparison of IPCC and CORINAIR Emission Inventory Programmes

Subject		IPCC	CORINAIR
Legal Base		FCCC Art. 4; 12	EEA Workprogramme Close links to EMEP (UNECE CLRTAP)
Objective		Reporting under FCCC	Reporting under various commitments
Geographical coverage		Parties to the Convention	European countries (EU and other)
Spatial resolution		National totals	Major emitters as point sources Other by administrative districts
Temporal resolution		Calendar year (annual totals)	Calendar year (annual totals)
Components	- common	CO_2, CH_4, N_2O, CO, NO_x, NMVOC	CO_2, CH_4, N_2O, CO, NO_x, NMVOC
	- further	—	SO_2, NH_3
	- for inclusion	Further Greenhouse Gases	Further GHGs, Heavy Metals, POPs
Sources		All anthropogenic	All anthropogenic and natural
Guiding principles concerning	- Internationality	Comparability across countries	Comparability across countries
	- Estimation GL*)	Optional	Optional
	- Reporting GL*)	Mandatory	Mandatory
Base of source categories	- Energy combustion	IEA Energy Statistics	Physical sources
	- Non-combustion	Physical sources	Physical sources
National totals reporting	- formatted	Both: activity rates and emission factors; IPCC only: emission levels	Both: activity rates and emission factors; IPCC only: emission levels
	- non-formatted	Description of basic data and methods	Description of basic data and methods
Reporting tools		Standard Data Tables and Summary Report Tables on paper or PC	Common PC System

*) Guidelines

Table 2. Comparison of Top Level Source Categories

Source Type			IPCC		CORINAIR*)
		Level 1		Level 1	
Anthropogenic					
Energy	— combustion			01	Public Energy
				02	Small Combustion
		1A	Fuel Combustion Activities	03	Industrial Combustion
				07	Road Transport
				08	Other Mobile Sources and Machinery
	— non-combustion	1B	Fugitive Emissions from Fuels	05	Extraction, Processing, Distribution of Fuels
Non-energy		2	Industrial Processes	04	Industrial Processes
		3	Product Use	06	Product Use
		4	Agriculture	10	Agriculture
		5	Land Use Change and Forestry	12	Land Use Change**)
		6	Waste	09	Waste
Natural			- · -	11	Nature

*) Modified versus CORINAIR 90　　**) Foreseen to be included

Table 3. Comparison of IPCC Energy Combustioin and IEA Energy Statistics Categories

Categories according to IEA: Level 1	2	3	4	5	6		Further Categories: Level 4	5	6	
1	A					Fuel Combustion Activities				
		1				Energy and Transformation				
		"	a			Electricity and Heat Production				
		"	"	i		Electricity Generation				
		"	"	"	x	Public				
		"	"	"	xx	Auto-generation				
		"	"	ii		Combined Heat and Power Generation				
		"	"	"					x	Public
		"	"	"					xx	Auto-generation
		"	"	iii		Heat Plants				
		"	b			Petroleum Refining				
		"	c			Other Energy and Transformation Ind.				
		"	"	i		Solid Fuel Transformation				
		"	"	ii		Other Energy Industries				
		2				Industry (Final Consumption)[x]				
		3				Transport				
		"	a			Civil Aviation				
		"	"					i		International Aviation (Bunkers)
		"	"					ii		Domestic
		"	b			Road Transport				
		"	"					i		Passenger Cars
		"	"					"	x	With 3-way Catalysts
		"	"					"	xx	Without 3-way Catalysts
		"	"					ii		Light Duty Trucks
		"	"					"	x	With 3-way Catalysts
		"	"					"	xx	Without 3-way Catalysts
		"	"					iii		Heavy Duty Vehicles
		"	"					iv		Motorcycles
		"	c			Railways				
		"	d			Navigation				
		"	"	i		International Marine (Bunkers)				
		"	"	ii		Internal Navigation				
		"	e			Other Transport				
		4				Small Combustion				
		"	a			Commercial, Institutional				
		"	b			Residential				
		"	c			Agriculture, Forestry, Fishing				
		"	"					i		Stationary
		"	"					ii		Off-road, other Machinery
		5				Other Combustion (Military)				
		"					a			Stationary
		"					b			Off-road, other Machinery

x) Subcategories omitted

category' issue was dealt with earlier. 'Industry' is another case in point. CORINAIR makes a clear distinction between the industrial and the public sector. IPCC, however, uses 'industry' in a broader sense (as does the IEA). To avoid misunderstandings in this paper, the term is used in the IPCC context in the normal sense, as a contrast to the public sector.

A further breakdown of categories was introduced by the IPCC for a number of reasons:

- to introduce a separate subcategory for auto-generation under combined heat and power generation as well. The public sector is thus consistently separated from the industrial sector. This issue will be discussed later in the context of Table 5.
- to differentiate between national and international energy use with regard to aviation,
- to consider relevant subsectors in road transport, and
- to distinguish stationary from mobile energy consumption under small-scale combustion.

A further breakdown as described in nos. 3 and 4 above is necessary in order to account for technological and operational parameters controlling emittants such as NO_x that are not mainly associated with the characteristics of the fuel. No such additions were made to the large combustion field where NO_x emissions likewise occur.

Table 4 shows the full hierarchy of source category levels and illustrates the conceptual divergencies. In both cases large combustion is divided into two 'sectors', yet according to different sectorial categories: an energy and transformation sector (1A1) versus the industry sector (1A2) on the IPCC side and the public (01) versus the industrial sector (03) on the other.

The collective term 'sector' is normally understood to comprise economically interlinked activities. This is how CORINAIR uses the term. The IPCC, however, adopts the energy balance concept of the IEA where the transformation sector is distinguished from the final consumption sector. Following this special definition, sectors represent stages of the energy flow system. As a consequence, certain industrial activities are included in the IPCC transformation sector.

With regard to sub-divisions the IPCC approach tracks the use of energy. That is why, for instance, electricity generation is separated from combined heat and power generation and individual industries are considered in the final consumption field. CORINAIR's main emphasis, however, is placed on the generation of emissions and therefore highlights technological parameters strongly influencing certain major emittants such as NO_x. This is why there is a distinction between combustion technologies and plant capacity classes up to various process furnaces.

Table 4. Comparison of IPCC and CORINAIR Large Combustion Source Categories

IPCC Level 1	2	3	4	5	6	IPCC	CORINAIR 90 Level 1	2	3	CORINAIR 90
1	A	1				Energy and Transformation	01			Public Combustion Plants
		"	a			Electricity and Heat Production		01		Power and Co-generation Plants
		"	"	i		Electricity Generation		"	01	> 300 MW
		"	"	"	x	Public		"	02	50-300 MW
		"	"	"	xx	Auto-generation		"	03	< 50 MW
		"	"	ii		Combined Heat and Power Generation		"	04	Gas Turbines
		"	"	"	x	Public		"	05	Stationary Engines
		"	"	"	xx	Auto-generation		02		District Heating Plants
		"	"	iii		Heat Plants		"	01	
								"	:	Subcategories as above
								"	05	
		"	b			Petroleum Refining	03			Industrial Combustion
		"	c			Other Energy and Transformation Industries		01		Boilers, Gas Turbines, Stationary Engines
		"	"	i		Solid Fuel Transformation		"	01	
		"	"	ii		Other Energy Industries		"	:	Subcategories as above
		2				Industry (Final Consumption)		"	05	
		"	a					02		Process Furnaces witht Contact[xx]
		"	b			Major Subcategories (significant		"	01	
		"	c			fuel consumers and emitters)		"	:	Various Processes
		"	:			by ISIC[x] Categories		"	04	
		"	:					03		Process Furnaces with Contact[xx]
								"	01	
								"	:	Various Processes
								"	23	

[x]) International Standard Industrial Classification of all Economic Activities, 1990
[xx]) Between flames and/or combustion gases and other process goods

The conceptual particularities of the two approaches in terms of sectorial categories can be studied by assigning energy use in large combustion plants to source categories as done in *Table 5*. Here the horizontal lines connect the respective types of plant with the matching categories according to IPCC and CORINAIR methodologies.

CORINAIR, as a plant by plant procedure, considers physical emitters as a whole — with a sectorial distinction between public and industrial installations — whereas the IPCC applies the principles of energy balances.

According to these principles

- electricity generation, both public and industrial, is treated as transformation,
- the allocation of heat generation depends on the types of industry and use:
  - public heat generation is considered as transformation
  - heat generation in energy and energy transformation industries is considered as transformation
  - heat generation in manufacturing industries is treated as transformation if the heat is sold to other consumers and as final consumption if used at the same establishment.

As a consequence, energy consumed by certain industrial co-generation plants must be attributed partly to transformation and partly to final consumption. Such a plant cannot, as a whole, be apportioned to a single IPCC source category.

Accordingly, industries as reported in energy balances do not include total energy consumption actually occurring in these industries if they generate electricity and/or sell heat. However, a large number of industries do so. For reasons of energy efficiency there is a growing tendency to promote co-generation in industry.

It was mentioned earlier that the introduction of a separate subcategory for auto-generation also under combined heat and power generation — which is not available from current IEA energy statistics — is a precondition for assigning IPCC emission data to the public and industrial sectors as used under CORINAIR. This can be tracked by proceeding from left to right on Table 5.

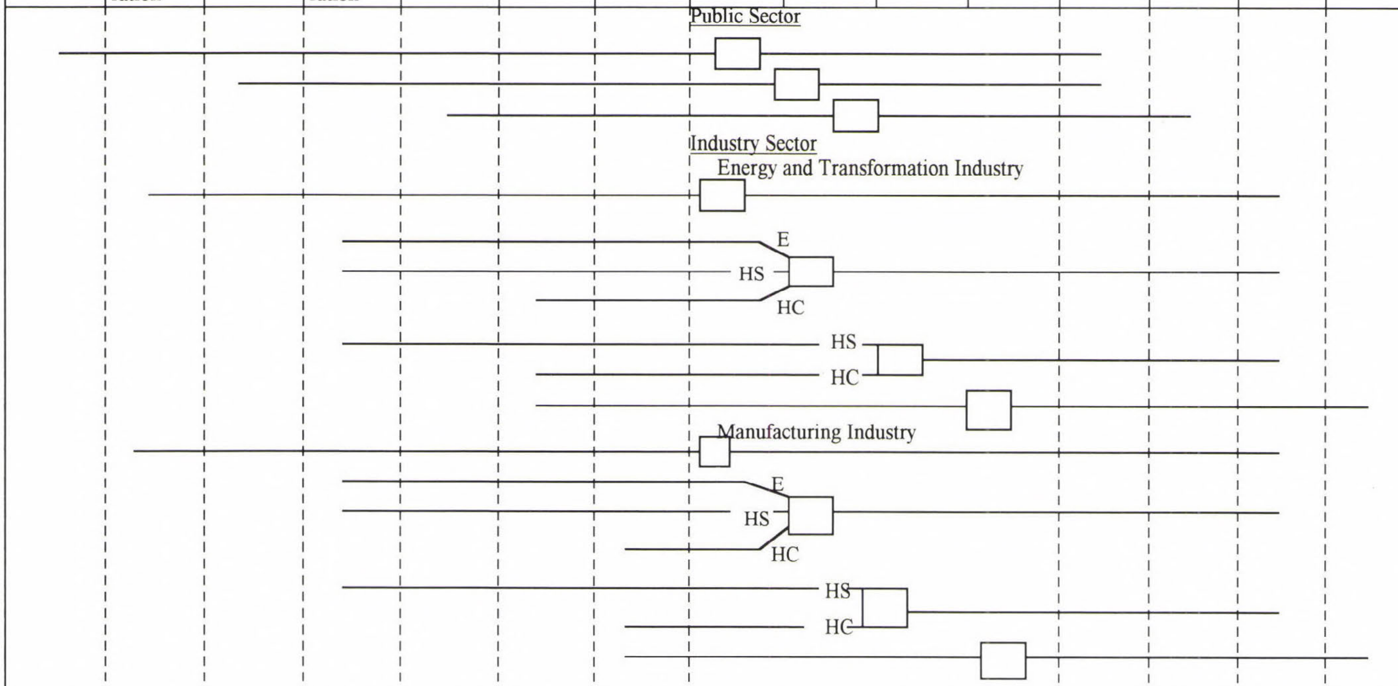
The correspondence between the two approaches to treating large combustion as discussed so far can be seen quite easily in *Table 6*. CORINAIR activities on the third level can be omitted here.

Heat plants correlate directly — the simplest case. For transferring public power and co-generation plants aggregating or disaggregating is required.

Highly controversial are the approaches to breaking down industry — by types of industry under the IPCC or by types of installation under CORINAIR. Under these conditions, transfer in both directions requires (i) complete aggregation and (ii) complete re-allocation. To arrive at auto-generation through

Table 5: Allocation of Energy Consumption in Large Combustion Plants to Source Categories

IPCC Energy and Transformation						Final Consumption	Large Combustion Plants Gas Turbines and Stationary Engines included				CORINAIR 90 Public Sector		CORINAIR 90 Industrial Sector	
Electricity Generation		Combined Heat and Power Generation		Heat Plants	Petroleum Refining; Other Energy and Transformation Industries	Industry	Power Plants	ombined Heat and Power Plants	Heat Plants	Process Furnaces	Power and Co-generation Plants	District Heating	Boilers, Gas Turbines, Stationary Engines	Process Furnaces
Public	Autogeneration	Public	Autogeneration											



Legend: E: Electricity; HS: Heat sold; HC: Heat consumed

Table 6. Correspondence between IPCC and CORINAIR Large Combustion Source Categories

IPCC	Level 3	Level 4	Level 5	Level 6	CORINAIR 90 Level 1	CORINAIR 90 Level 2	CORINAIR 90
Energy and Transformation	1				01		Public Combustion Plants
Electricity and Heat Production	"	a					
Electricity Generation	"	"	i				
Public	"	"	"	x			
Auto-generation	"	"	"	xx	"	01	Power and Co-generation Plants
Combined Heat and Power Generation	"	"	ii				
Public	"	"	"	x			
Auto-generation	"	"	"	xx			
Heat Plants	"	"	iii		"	02	District Heating Plants
Petroleum Refining	"	b					
Other Energy and Transformation Ind.	"	c					
Solid Fuel Transformation	"	"	i				
Other Energy Industries	"	"	ii				
Industry (Final Consumption)	2				03		Industrial Combustion
A	"	a			"	01	Boilers, Gas Turbines, Stationary Engines
B	"	b			"	02	Process Furnaces without Contact
C Major ISIC Subcategories	"	c			"	03	Process Furnaces with Contact
:	"	:					
:	"	:					

transfer from the CORINAIR format one has to go through three stages: breakdown (i) of total industry by types and (ii) of various major industries by auto-generation and heat consumption and (iii) aggregation of auto-generation. These circumstances render data transfer between the CORINAIR and the IPCC formats difficult.

4. Proposals for Reconciliation

About 30 European countries have joined the CORINAIR 90 programme. To facilitate data transfer from CORINAIR 90 inventories to the IPCC format under the auspices of the first national communication of FCCC parties for 1994 a PC programme was developed. Yet, because of many incompatibilities, including those discussed above, this interface does not work automatically. To become operational it must be 'fed' with country-specific supplementary data.

To overcome these obstacles a staged harmonization initiative is needed. Therefore, a two stage programme is proposed as follows:

- Stage I Objectives: Automatic data transfer from the CORINAIR to the IPCC format meeting level 3 requirements
  Action required:
  - agree on common principal definitions
  - adjust CORINAIR source categories
- Stage II Objectives: Common source categories of the two programmes
  Action required:
  - agree on common source categories
  - break down energy statistics categories to match IPCC and CORINAIR requirements.

Differences in breaking down large combustion energy use are not the only problem between the IPCC and CORINAIR programmes. Common definitions are still needed for:

- Road transport with respect to spatial allocation. Here CORINAIR with a view to the input requirements of atmospheric dispersion models applies the principle of territoriality (emission allocation according to fuel consumption) whereas the IPCC is bound to the principle of political responsibility (allocation according to fuel sale).
- Civil national aviation: CORINAIR so far covers airports only, whereas the IPCC requires total domestic aviation.
- National navigation: CORINAIR includes harbours and has a specific definition of national sea traffic without a geographical limitation whereas the IPCC only considers coastal navigation.

Table 7 shows how CORINAIR large combustion source categories could be modified to better fit into IPCC level 3. This limited resolution appears to be sufficient at present because the Standard Data Tables of the IPCC Reporting Instructions do not require more detailed treatment.

Table 7. Harmonisation Stage I
CORINAIR Large Combustion Categories Adjusted to Match IPCC Level 3

CORINAIR 90	Level 1	Level 2	Structural Change	CORINAIR 94 Proposal	Data Flow	IPCC Level 1	IPCC Level 2	IPCC Level 3	IPCC
				Public Sector					
Public Power and Co-generation Plants	01	01	→	Power and Co-generation Plants	→				
District Heating	"	02	→	District Heating Plants	→				
				Industry Sector	→	1	A	1	Energy and Transformation
			→	Energy and Transformation Industry	→				
Industrial Boilers, Gas Turbines and Stationary Engines	03	01	→	Manufacturing Industry					
			→	– Auto-generation	→				
			→	– Heat Consumed	→				
					→	1	A	2	Industry (Final Consumption)
Process Furnaces	03 "	02 03	⇶	Process Furnaces	⇶				

⇶ : By industries

The few changes necessary to convert CORINAIR 90 into CORINAIR 94 involve a separation of transformation from manufacturing industries and a distinction of auto-generation and use of heat in the manufacturing industries.

As CORINAIR process furnaces are available by different industries a grouping into manufacturing industries (to be assigned to final consumption) and transformation industries (to be assigned to energy and transformation) does not cause any difficulties.

The common source category split as targeted under stage II and outlayed in *Table 8* would result from a combination of both current category systems.

As shown here, CORINAIR would have to move from the left hand side and IPCC from the right hand side to meet in the middle. CORINAIR, starting from the 94 version (as proposed) would have to separate public power from co-generation plants and to deal with industries — transformation and manufacturing — individually together with a distinction of auto-generation and heat consumption shares.

The IPCC, on the other hand, would be expected to allocate auto-generation to the various industries and to sort out process furnaces from individual industry totals. Another step is not visualised explicitly in Table 8 is that the CORINAIR concept requires a differentiation of combustion plants by types of installation.

With a view to the use of emission inventories under IPCC conventions for strategy development in the context of economic models first priority might be given to an allocation of emissions to the industrial sector as a whole and to selected major industries in the sense of covering total energy demand. This step would reconcile current IPCC sectors — transformation versus final consumption — with the economic understanding of the sectorial concept.

It would be most helpful if the *IEA* (1992) could, in addition to its standard publications, prepare reference energy statistics specifically designed to meet emission inventory requirements.

5. Conclusion

The following conclusions and recommendations can be derived:

- Harmonization would be of great benefit to the international emission inventory community and to related environmental activities.
- Harmonization must be considered as technically feasible.
- Harmonization could proceed in stages.
- Harmonization should attempt to result in common source categories as soon as possible.
- Harmonization should eventually lead to one supranational emission inventory system.

Table 8. Harmonisation Stage II
Common Large Combustion Categories Matching CORINAIR and IPCC Formats

CORINAIR 94 Stage I Proposal	Structural Change	Common Approach Proposal	Structural Change	IPCC Level 3	4	5	6	IPCC
Public Sector		Public Sector						
				1	a	i		Electricity Generation
		Power Plants		"	"	"	x	Public
Public Power and Co-generation Plants				"	"	"	xx	Auto-generation
				"	"	ii		Combined Heat and Power Generation
		Co-generation Plants		"	"	"	x	Public
				"	"	"	xx	Auto-generation
District Heating Plants		District Heating Plants		"	"	iii		Heat Plants
Industry Sector		Industry Sector (by major industries)						
		Boilers, Gas Turbines and Stationary Engines						
Manufacturing Industry Auto-generation								
		– Auto-generation						
Energy and Trans-formation Industry								
		– Heat Consumed						
Manufacturing Industry Heat Consumed				"	b			Petroleum Refining
				"	c			Other Energy and Trans-formation Industries
				2				Industry (Final Consumption)
Process Furnaces		Process Furnaces			a			
					b			
					c			Major Subcategories
					⋮			

⇶ : By industries

References

CORINAIR, 1993: Source Category Split SNAP 90, as of 13.07.1993.

IEA, 1992: Energy Statistics of OECD Countries 1989-1990, OECD, Paris.

IPCC, 1995: Guidelines for National Greenhouse Gas Inventories, Vol. I: Greenhouse Gas Inventory Reporting Instructions.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Global Emissions of Fluorocarbons and SF_6 (1986–2100)

Carolien Kroeze

Wageningen Institute for Environment and Climate Studies, Agricultural University, P.O. Box 9101, 6700 HB Wageningen, The Netherlands

Abstract—This article presents scenarios for future emissions of several fluorocarbons (HFCs, PFCs, FICs) and SF_6. These are used as substitutes for compounds that will be phased out when the Montreal Protocol on substances that deplete the ozone layer will be implemented.

The *reference scenario* assumes implementation of the Montreal Protocol, and no further regulations for fluorocarbons and SF_6. By the year 2040, emissions of HFCs, PFCs, FICs, and SF_6 will equal 14 percent of the 1990 global CO_2 emissions in this scenario. A reduction to 8 percent is achieved by assuming maximum emission control through better housekeeping, recycling, and destruction of fluorocarbon wastes, part of which may be realized without additional regulations. It is therefore concluded that, without specific fluorocarbon policy, the 2040 fluorocarbon emissions could equal 8–14 percent of the 1990 CO_2 emissions, and are probably at the higher end of this range.

In the *closed applications only scenario* the use of HFCs, PFCs, FICs, and SF_6 is restricted to stationary cooling and closed-foam blowing, which are applications with the lowest annual loss rates. The resulting emissions are 40–50 percent lower than in the reference scenario.

The *low-GWP scenario* assumes that only compounds, or blends, are used with a GWP less than 250. This results in a 90 percent reduction in CO_2-equivalent emissions relative to the reference scenario.

Key-words: fluorocarbons, HFCs, PFCs, FICs, SF_6, Montreal Protocol.

1. Introduction

Halocarbons are chlorinated, fluorinated, brominated, or iodated carbon compounds. In general they are powerful greenhouse gases (*IPCC*, 1994). Most chlorinated carbon compounds have large ozone depleting potentials and are therefore regulated under the Montreal Protocol on substances that deplete the ozone layer.

The present study focuses on the climatic impact of fluorinated compounds that are not regulated under the Montreal Protocol. These include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), fluoroiodocarbons (FICs), and sulphur hexafluoride (SF_6) and are mainly used as substitutes for compounds that will be phased out when the Montreal Protocol is implemented.

The Montreal Protocol is an international agreement to protect the ozone layer (*UNEP*, 1987). The first version, of 1987, has been reinforced twice (*UNEP*, 1991, 1992). When the 1992 amendments are implemented, use of chlorofluorocarbons (CFCs), 1,1,1 trichloroethane (CH_3CCl_3) and chlorobromocarbons (halons) will be stopped before the year 1996. Hydrochlorofluorocarbons (HCFCs), which are used as substitutes for CFCs and halons, are to be phased out by 2030. Many European countries have already stopped using CFCs and halons, and will phase out HCFCs by 2015.

This paper presents scenarios for global emissions of several fluorocarbons and SF_6 for the period 1986–2100. Actual emissions are presented, taking into account the delay between use and emissions. The scenarios assume implementation of the Montreal Protocol, with and without additional regulations for fluorocarbons.

Emissions of fluorinated compounds are calculated in four steps, estimating:

1. Pre-Montreal demand, that is, the future, worldwide demand for halocarbons and SF_6 as would have been the case without the Montreal Protocol;
2. The amount of halocarbons to be replaced, that is, the difference between the pre-Montreal demand and the envisaged use when the 1992 Copenhagen amendments to the Montreal Protocol will be realized;
3. Future use of fluorocarbons and SF_6 for a situation without further regulations, based on substitution rates for each halocarbon in each application;
4. Emissions for a number of scenarios, assuming different levels of control.

Step 1. Pre-Montreal Demand for Halocarbons

The scenario assumptions for pre-Montreal demand are described in detail in *Kroeze* (1995). The *pre-Montreal demand* for halocarbons is defined here as the future demand for halocarbons for a situation without the Montreal Protocol. It is assumed here that the pre-Montreal demand for halocarbons will not stabilize in the near future (*Table 1*). The pre-Montreal demand is estimated assuming that the average per capita pre-Montreal use in industrialized countries (averaged total for OECD, Eastern Europe, and the Former Soviet Union) stabilizes at the 1986 level. Worldwide demand for halocarbons in 2000 and 2040 is based on *Hammitt et al.* (1987). For the period 2040 to 2100, it is assumed that the the average per capita pre-Montreal demand in nonindustrialized world regions linearly increases to the averaged 1986 level of industrialized countries. Thus by 2100 the globally-averaged pre-Montreal per capita use equals that of the 1986 level in industrialized countries. Although this crude assumption does not take into account possible latitudinal differences, it is in line with the assumed increase of GNP in different world regions, as presented in the IPCC 1992 scenarios (*Pepper et al.,* 1992). The world population is assumed to increase as in scenario IS92a of IPCC (*Pepper et al.,* 1992).

Table 1. Pre-Montreal demand (kt y^{-1}) for CFCs, halons, CH_3CCl_3 and HCFCs (non-substitute use) and expected use when the 1992 Montreal Protocol is realized (reference scenario). The difference between pre-Montreal demand and the reference scenario is the amount to be replaced

Year	CFCs, halons CH_3CCl_3		HCFC-22, HCFC-142b	
	Pre-Montreal demand	Reference scenario[5]	Pre-Montreal demand	Reference scenario[5]
1986[1]	1718	1718	189	189
2000[2]	2540	633	266	266
2005[3]	3037	0	298	177
2015[3]	4032	0	362	0
2040[2]	6520	0	521	0
2100[4]	15181	0	1646	0

[1] Alternative Fluorocarbon Environmental Acceptability Study (AFEAS), 1993, 1994 (non-feedstock consumption), non-reporting companies estimated by Olivier (personal communication); for gases not reported by AFEAS the 1985 data from *Hammitt et al.* (1987) are used; [2] from *Hammitt et al.* (1987), except CFC-114 and CFC-115, which are from *Kroeze* and *Reijnders* (1992); for HCFC-22 and -142b the growth rate of CFCs is adopted; HCFC-142b in 2000 is assumed to be the same as 1992 according to AFEAS (1993); [3] linearly interpolated; [4] based on global average per capita consumption as in 1986 in industrialized countries (*Kroeze,* 1995); [5] assuming that by 2000 use of CFCs, halons and CH_3CCl_3 is restricted to less developed countries, that no CFC-114 and -115 are used by 2000 and that HCFCs are phased out by 2015.

Step 2. Halocarbons to be Replaced

The pre-Montreal demand for halocarbons increases throughout the next century (Table 1). Up to the early 1990s, most of the demand was met by CFCs, halons, and CH_3CCl_3. This will change dramatically as these compounds are to be phased out as a result of the Montreal Protocol. It is assumed here that use of CFCs, halons, and CH_3CCl_3 will be stopped before 2000 in industrialized countries and by 2005 in developing countries. It is furthermore assumed that use of HCFCs will be stopped in 2015 worldwide. The latter may be an optimistic assumption, because the Montreal Protocol allows use up to 2030. However, an earlier phase-out is envisaged by the industrial Alliance for Responsible Atmospheric Policy (*Fay,* 1995). As a result, the demand for alternatives by 2015 amounts to about 4000 kt in the reference scenario (Table 1).

The breakdown in use per application in the pre-Montreal situation (not shown here) is estimated assuming that the breakdown per gas per application will remain at the 1986 level as reported by AFEAS (1993, 1994), or if not presented by AFEAS, by *Kroeze* and *Reijnders* (1992). It is assumed that 50 percent of the CFC-12 used as a cooling agent is used in mobile air conditioning, that HCFC-22 is exclusively used for stationary refrigeration and CH_3CCl_3 for cleaning.

Step 3. Use of Fluorocarbons and SF_6 in the Reference Scenario

Substitution rates, that is, replacement of the demand for CFCs, halons, and CH_3CCl_3 as would have been the case without the Montreal Protocol by HFCs, PFCs, FICs, and SF_6, are estimated for the most important applications (*Table 2*). It is estimated that, between 2005–2015, without further regulations, about 20 percent of the demand for CFCs, halons, and CH_3CCl_3 as would have been the case without the Montreal Protocol, will be replaced by about 25 different HFCs, PFCs, FICs and SF_6 (Table 2). Substitution rates for 2005–2015 are 9–11 percent for aerosols, less than 5 percent for cleaning, 1–2 percent for open-foam blowing, 40–45 percent for closed-foam blowing, more than 50 percent for stationary refrigeration, less than 75 percent for mobile air conditioning, 45–50 percent for fixed fire extinguishing and 30 percent for other. In addition, 75 percent of the historical HCFC-22 market may be replaced by HFCs after an HCFC phase-out.

Table 3 shows the global use of fluorocarbons and SF_6 in the reference scenario (that is, the scenario assuming no further regulations), based on the amount to be replaced (Table 1) and substitution rates (Table 2).

The nonregulated fluorocarbons are not only used as substitutes. Several have their own historical market. By 1986, about 200 kt of HCFCs, PFCs, and SF_6 were used annually (Table 3). It is tentatively assumed in the reference scenario, that the historical use of PFCs and SF_6 will double during the next century. For PFCs this may be an overestimation, because new HFC liquids in development may take over part of the market. The 2000 level is mainly based on *Ko et al.* (1993).

In general, the estimates for future use are in reasonable agreement with other studies. In 2000, about 645 kt of HCFCs and HFCs are used in the reference scenario, which is in good agreement with the 625 kt as estimated by the industrial Alliance for Responsible Atmospheric Policy (*Fay*, 1995). *Fay* (1995) estimated use of HFCs and HCFCs in 2000 at 325 kt and 300 kt, respectively, as opposed to 240 and 405 kt presented in the reference scenario. *UNEP* (1994) estimated HCFC use in 2000 at 300–335 kt. Thus for the year 2000 the use of HCFCs may be overestimated in the reference scenario and that of HFCs underestimated. The reference scenario assumes that a shift from HCFCs to HFCs will not start before 2000, while UNEP and ARAP seem to assume this will happen earlier. On the other hand, the reference scenario assumes a total phase-out of HCFCs by 2015, which may in fact happen later.

Table 2. Worldwide substitution of regulated compounds by HFCs, HCFCs, PFCs, FICs and SF_6; from *Kroeze* (1995), mostly based on *Fay* (1995) and *DuPont* (1994)

Application	Historical use	Halocarbon substitute	Estimated replacement		
			in 2000[1]	until 2005[2]	from 2015[3]
			percent of 1986 use	percent of pre-Montreal demand to be replaced	
Aerosol	CFC-11,-12,-114	HCFC-22		1.5	-
		HCFC-141b		1.5	-
		HCFC-142b		1.5	-
		HFC-134a		2	3
		HFC-152a		2	3
		HFC-227ea		2	3
		Total	**15**	**11**	**9**
Cleaning/drying	CFC-113, CH_3CCl_3	HCFC-141b		1	-
		HCFC-123		1	-
		HCFC-225ca/cb		1	-
		HFC-43-10		0.5	2[6]
		PFC		0.5	2[6]
		Total	**5**	**4**	**4**
Open cell foams	CFC-11,-12,-114	HCFC-22		0.5	-
		HCFC-141b		0.5	-
		HFC-134a		0.5	0.5
		HFC-152a		0.5	0.5
		Total	**<5**	**2**	**1**
Closed cell foams	CFC-11,-12,-113,-114	HCFC-22		5	-
		HCFC-141b		15	-
		HCFC-142b		15	-
		HFC-134a		0.6	2.5
		HFC-143a		1.25	5
		HFC-152a		0.6	2.5
		HFC-236fa		2.5	10
		HFC-245ca		2.5	10
		HFC-356		2.5	10
		Total	**60**	**45**	**40**

Continued Table 2.

Application	Historical use	Halocarbon substitute	Estimated replacement		
			in 2000[1]	until 2005[2]	from 2015[3]
			percent of 1986 use	percent of pre-Montreal demand to be replaced	
Stationary refrigeration	DFC-11,-12,-113,-114,-115	HCFC-22		3	-
		HCFC-123		3	-
		HCFC-124		3	-
		HFC-23		2.5	3
		HFC-32		2.5	3
		HFC-134a		25	30
		HFC-125		2.5	3
		HFC-143a		2.5	3
		HFC-152a		2.5	3
		HFC-227ea		2.5	3
		PFC		2	2
		Total	**>75**	**50**	**50**
Stationary refrigeration	HCFC-22	HFC-32	-	-	15
		HFC-134a	-	-	15
		HFC-152a	-	-	15
		HFC-143a	-	-	15
		HFC-125	-	-	15
		Total	**0**	**0**	**75**
Mobile air conditioning	CFC-12	HFC-134a		75	75
		Total	**100**	**75**	**75**
Fire extinguishing (fixed systems)[7]	Halon 1301[7]	HCFC-123		3	-
		HCFC-124		3	-
		HFC-23		3	3
		HFC-125		3	3
		HFC-134a		3	3
		HFC-227ea		25	25
		PFCs		3	3
		FICs		3	3
		SF_6		3	3
		Total	**50-80**	**50**	**45**
Other	CFC-11,-12	HFC-125		10	10
		HFC-134a		10	10
		HFC-227ea		10	10
		Total	**<50**	**30**	**30**
Total[4]	**CFCs, halons, CH_3CCl_3 HCFCs**		**35**	**21**	**18** **75[5]**

Continued Table 2.

[1] fluorocarbon market in 2000 as percent of the 1986 market, mainly based on *Fay* (1995) and *DuPont* (1994); [2] fluorocarbon market as percent of the pre-Montreal demand (i.e. future demand as it would have been without Montreal Protocol); totals per applications are deduced from [1] assuming a 45 percent increase in pre-Montreal use of CFCs and halons between 1986 and 2000; use of specific fluorocarbons per application is described in *Kroeze* (1995); [3] assuming an HCFC phaseout by 2015; [4] estimated in *Kroeze* (1995); [5] <80 percent according to *Fay* (1995); [6] may be partly replaced by new HFC liquids in development; [7] it is assumed here that fluorocarbons only replace halons in fixed systems (*Stamp*, personal communication); replacement in portables is less than 2 percent of the pre-Montreal demand (some HCFC-123).

In 2015, 340 kt of HFC-134a is used in refrigeration in the reference scenario. This is in reasonable agreement with the 300 kt by 2020, as envisaged by *McCulloch* (1994a). McCulloch's estimate of 90 kt of HFC-32 used as a cooling agent by 2020 exceeds the 60 kt as envisaged in the reference scenario for 2015.

Finally, in 2040 the use of HFCs amounts to 1440 kt in the reference scenario (Table 3). Again, this is in good agreement with the ARAP estimate of 1100–1400 kt for the year 2035 (*Fay, 1995*).

Table 3. Use of HCFCs, HFCs, PFCs, FICs and SF_6 in kt y^{-1} the reference scenario 1986–2100 (non-feedstock use, i.e. not used as intermediate). A distinction is made between historical use (i.e. in applications that existed before the Montreal Protocol) and use as substitute for compounds to be phased out

Year	HCFCs		HFCs	PFCs, FICs, SF_6		Total
	Historical use[2]	Use as substitute	Use as subsitute	Historical use	Use as substitute	
1986[1]	189	0	0	15	0	204
2000	266	140	241	15	9	671
2005	178	214	352	16	14	773
2015	0	0	918	17	50	985
2040	0	0	1439	21	80	1540
2100	0	0	4019	30	169	4218

[1] AFEAS, 1993, 1994 (non-feedstock consumption), non-reporting companies estimated by *Olivier* (personal communication); [2] data up to 1990 are from AFEAS, 1993; for future years assuming that per capita consumption stabilizes at the 1986 level of industrialized countries; it is assumed that in 1970 the 'stock' of unreleased HCFC-22 was 117 kt (based on *AFEAS*, 1993).

Table 4 presents a breakdown in use of halocarbons per application by 2040. Most important applications are cooling (60 percent), closed cell blowing (19 percent) and cleaning (8 percent). The most important halocarbon to be used is HFC-134a (40 percent). Second most important are HFC-125, HFC-143a and HFC-152a (each 7–9 percent).

Table 4. Use (non-feedstock) on HFCs, PFCs, FICs and SF_6 in kt y^{-1} the reference scenario in 2040 (result of 'step 3'; see text)

HFC–	23	32	125	134a	143a	152a	227ea	236fa	245ca	356	43-10mee	PFC	FIC	SF_6	Total
Aerosol				27		27	27								82
Cleaning											65	65			129
Open cell				2		2									4
Closed cell				19	37	19		75	75	75					299
Stationary cooling	17	86	86	240	86	86	17					11			630
Mobile air conditioning				301											301
Fire extinguishing	1		1	1			11					1	1	1	19
Other[1]			18	18			18					14		7	75
Total	18	86	106	608	124	134	73	75	75	75	65	91	1	8	1539

[1] Including historical use of PFCs and SF_6; [2] PFCs may be replaced by HFC liquids in development

Step 4. Scenarios for Future Emissions

Emissions are presented here for a reference scenario; a closed applications only scenario, in which use of halocarbons and SF_6 is restricted to closed foam blowing and stationary refrigeration, being applications with relatively low annual loss rates; and a low GWP compounds only scenario, in which use of halocarbons is restricted to halocarbons with relatively low global warming potentials (*Table 5*). These three scenarios are presented for two variations: with and without emission control. In the emission control variations, good housekeeping is realized with maximum recycling and destruction of halocarbon wastes.

The scenarios present actual emissions. Actual emissions differ from the annual use, because emissions may be delayed. For a number of applications, emissions occur almost immediately. However, when compounds are used as cooling or blowing agents, emissions may be delayed by many years. The method used to calculate emissions is described in *Kroeze* (1995) and based on *AFEAS* (1993, 1994), *McCulloch* (1992, 1994a, 1994b), *Gamlen et al.* (1986), *McCarthy et al.* (1977), *Fisher* and *Midgley* (1993), and *Midgley* and *Fisher* (1993).

Table 6 and *Figs. 1* and *2* summarize global emissions for the period 1990–2100 expressed in CO_2-equivalents. For calculating CO_2-equivalent emissions, the direct global warming potentials over 100 years from IPCC (1994) were used. GWPs for HCFC-225ca/cb, HFC-356, PFCs, and FICs are assumed to be 350 (average of ca and cb), 1300 (as HFC-134a), 9400 (average of PFCs), and 10 (tentatively estimated as twice the GWP of CF_3I), respectively.

In the reference scenario, total annual emissions of HFCs, PFCs, FICs, and SF_6 amount to about 165 kt by 2000, which is considerably less than the 265 kt used in that year (Table 3). This difference is caused by the delay between use and emissions. Since almost 80 percent of the HFCs are used in cooling and closed foam blowing, emissions lag behind use.

In the reference scenario, global emissions of HCFCs gradually decline to zero, while emissions of HFCs, PFCs, FICs, and SF_6 continue to increase (Fig. 1). By 2040, their emissions equal 3800 Mton of CO_2-equivalents per year (Fig. 2; *Table 6*). Maximum emissions control could reduce these emissions by 40–45 percent. These emissions equal to 14 percent and 8 percent of the 1990 global CO_2 emission (27 Gt CO_2 y^{-1}; *Houghton et al.,* 1992), respectively. Some recycling is being implemented presently. Therefore it can be concluded that without specific policy, fluorocarbon emissions may, by 2040, equal to 8–14 percent of the global warming potential of 1990 global CO_2 emissions and may be at the higher end of this range, because certainly not all of the potential emission control will be implemented without further regulations. It is obvious that if global CO_2 emissions increase, the relative contribution of halocarbons to global warming would decrease accordingly.

Table 5. Overview of scenario assumptions

(i) Reference scenario

- Pre-Montreal demand is as in Table 1: worldwide per capita pre-Montreal demand gradually increases to the 1986 level in industrialized countries.
- The 1992 Montreal Protocol is implemented: use of CFCs in industrialized countries is stopped before 2000 and in the rest of the world in 2005. Use of HCFCs increases unrestrictedly until 2000 and is 0 from 2015 (changes between these years are linear).
- About 20 percent of CFCs, halons and CH_3CCl_3 to be replaced and 75 percent of the historical use of HCFC-22 to be replaced are met by HFC, PFCs, FICs and SF_6 (Table 2). These percentages take into account the currently observed trend that less refrigerant is needed per unit cooling. Substitution starts from 1995 and 2.5 percent of the cooling agents are used for household appliances.
- Actual emissions are calculated as described in *Kroeze* (1995). New markets for halocarbons are ignored.
- In 'reference + MAX' emission control through better housekeeping, recycling and destruction of halocarbon wastes is maximized[1].

(ii) Closed applications only

- This scenario differs from the reference scenario in that use of halocarbons is only allowed in stationary refrigeration and closed foam blowing, which are applications with relatively low annual loss rates (*Kroeze*, 1995).
- In 'closed applications only + MAX' emission control through better housekeeping, recycling and destruction of halocarbon wastes is maximized[1].

(iii) Low GWP compounds only

- This scenario differs from the reference scenario in that only compounds or blends are used with a relatively low GWP. Thus the total amount used per application is the same as in the reference scenario, but the substitutes used are pure or blended mixtures having a GWP less than 250. An average GWP of 250 is about 90 percent lower than the average GWP of halocarbons emitted in the reference scenario (Table 6). This implies that for 90 percent of the halocarbons used in the reference scenario, low-GWP alternatives are available. In *Kroeze* (1995) it is concluded that for most applications non-halocarbons could, in the near future, replace 90–100 percent of the demand for halocarbons. If, in addition, low-GWP HFCs are allowed, an upper limit of 250 would seem within reach. Halocarbons with a direct GWP less than 250 include HCFC-123, HCFC-225ca, HFC-152a and the FICs.
- In 'low-GWP compounds only + MAX' emission control through better housekeeping, recycling and destruction of halocarbon wastes is maximized[1].

[1] maximum emission control variants to scenarios (+ MAX) assume maximum effort to reduce emissions by good housekeeping, recycling and destruction of halocarbon wastes. The effect thereof is described in *Kroeze* (1995). The general assumptions are that leakage is prevented as much as possible and 80 percent of the halocarbons and SF_6 that is available after use is recycled or destroyed. Such severe emission control will not happen without further regulation.

Table 6. Worldwide emissions of HCFCs, HFCs, PFCs, FICs and SF_6 (in CO_2-equivalents), the average GWP of the mix emitted and total CO_2-equivalent emissions expressed as percent of the 1990 CO_2 emissions for the reference scenario (reference), closed applications only scenario (closed only) and low GWP compounds only scenario (GWP < 250); all three scenarios are presented for a situation without emission control (no control) and for a situation in which emission control by better housekeeping, recycling and destruction of halocarbon wastes is maximized (+ MAX)

Year	Total CO_2-eq. emission ($Mt\ y^{-1}$)			Average GWP			Percent of 1990 global CO_2 emissions		
	reference	closed only	GWP < 250	reference	closed only	GWP < 250	reference	closed only	GWP < 250
	no control	no control	no control	no control	no control	no control	no control	no control	no control
2000	1022	575	120	2139	1798	250	4	2	<1
2005	1378	744	168	2048	1854	250	5	3	<1
2015	2335	1210	236	2474	2177	250	9	4	<1
2040	3798	2103	356	2671	2504	250	14	8	1
2100	9382	5906	943	2488	2437	250	35	22	3
	+ MAX	+ MAX	+ MAX	+ MAX	+ MAX	+ MAX	+ MAX	+ MAX	+ MAX.
2000	541	190	50	2752	1808	250	2	1	<1
2005	783	308	83	2345	1836	250	3	1	<1
2015	1319	632	138	2390	2124	250	5	2	<1
2040	2169	1175	210	2587	2602	250	8	4	<1
2100	5278	3251	543	2432	2550	250	20	12	2

Restricting use of halocarbons to closed applications could result in emissions that are 40–50 percent lower than in the reference scenario. This illustrates the fact that applications with low annual emissions may, when the equipment lifetime is long, emit large quantities of halocarbons. An 'open' application-like cleaning probably offers as many possibilities to reduce emissions as the 'closed' applications considered here. Restricting use to closed applications is most effective when emission control is maximized.

Using only compounds with a low GWP reduces emissions expressed in CO_2-equivalents by about 90 percent relative to the reference scenario. Most of the HFCs used in this scenario may be blended, which may make recycling difficult.

The average Global Warming Potential of the mix of halocarbons emitted increases in most scenarios between the years 2000 and 2040 (Table 6). In the reference scenario without emission control, the increase is about 25 percent;

in the closed-applications-only scenario, about 40 percent. This is mainly the result of the HCFC phase-out early next century. The HFCs substitutes have higher GWPs than the HCFCs they replace. Restricting use of halocarbons to stationary cooling and closed foam blowing reduces the average GWP by about 10–25 percent during the first decades of the next century.

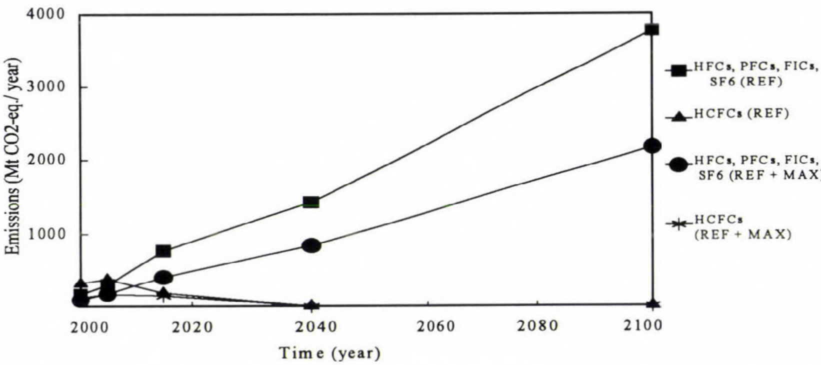


Fig. 1. Emissions of HCFCs and HFCs (including PFCs, FICs and SF_6) in the reference scenario with maximum (+ MAX) and without emission control in kt y^{-1}.

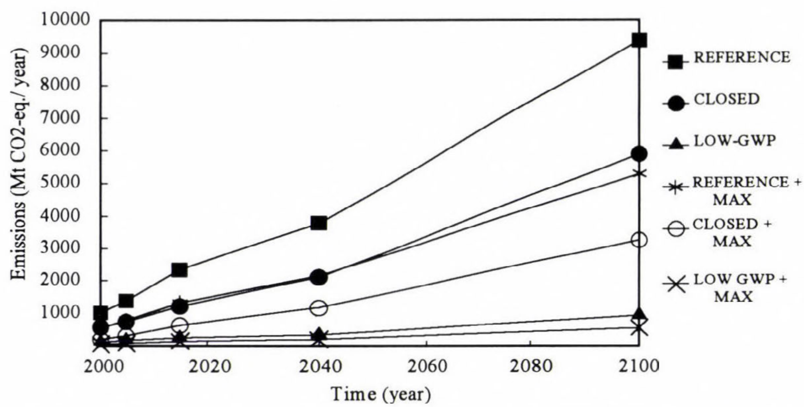


Fig. 2. Emissions of HCFCs, HFCs, PFCs, FICs and SF_6 in the reference scenario, closed applications only scenario and low GWP compounds only scenario, all three with maximum (+ MAX) and without emission control.

2. Conclusions

This study surveys emissions of halocarbons for the period 1986–2100. Emissions for several scenarios are presented here. The reference scenario reflects a situation without specific regulations beyond Montreal for HFCs, PFCs, FICs, and SF_6. In this scenario, global use of HFCs inreases to about 1440 kt in 2040. When CFCs and HCFCs are phased out, the most important halocarbon applications are stationary cooling (60 percent), closed foam (19 percent), and cleaning (8 percent). The most widely used halocarbon is HFC-134a (40 percent). Second most important are HFC-125, HFC-143a, and HFC-152a (7–9 percent each).

Without specific policy, emissions of HFCs, PFCs, FICs, and SF_6 may, by 2040, equal to 8–14 percent of the 1990 global CO_2 emissions and may be at the higher end of this range because the lower end assumes maximum emission control, which will not be fully implemented without further regulations. The results of this study are within the range of an earlier RIVM estimate of 7–17 percent (*Kroeze*, 1994).

Maximum emission control through better housekeeping, recycling, and destruction of halocarbon wastes reduces CO_2-equivalent emissions by about 40–45 percent in the reference scenario.

The average GWP of the halocarbon mix emitted increases by about 25 percent between 2005 and 2040 in the reference scenario. This is mainly the result of the HCFC phase-out: the HFCs used have higher GWPs than the HCFCs they replace.

Restricting use to stationary cooling and closed foam blowing, which are applications with relatively low annual loss rates, decreases halocarbon emissions by about 40–50 percent relative to the reference scenario. Restricting use to closed applications is most effective when emission control is maximized.

When only compounds are used with global warming potentials lower than 250, CO_2-equivalent emissions are 90 percent lower than in the reference scenario.

Acknowledgements—This study was performed at the National Institute of Public Health and Environmental Protection in the Netherlands, and commissioned by the Air and Energy Directorate of the Directorate-General for Environmental Protection of the Dutch Ministry of Housing, Physical Planning and Environment (project 773001; RIVM report no. 773001007). The author gratefully acknowledges *A.R. Van Amstel, R.A.W. Albers, H. Benjamins, A.P.T.J. Coens, E. Cook, C.J.H. Cozijnsen, M.G.J. den Elzen, K.J. Fay, R. de Goeij, J. Janssen, J.G.J. Olivier, M. Stamp, G.J.M. Velders, F.A. Vogelsberg, R. Wams,* and *B. Weenink* for comments or providing valuable information.

References

AFEAS, 1993: *Production, sales and atmospheric release of fluorocarbons through 1992.*

AFEAS, 1994: *Historic production, sales and atmospheric release of HCFC-142b.*

DuPont, 1994: *Information presented at the tenth meeting of the International Negotiating Committee, Geneva, 27 August 1994*: DuPont, USA.

Fay, K.J., 1995: *Critique of articles by C. Kroeze concerning potential effect of HFC policy on global greenhouse gas emissions.* Alliance for Responsible Atmospheric Policy and the International Climate Change Partnership. Arlington, Virginia, USA.

Fisher, D.A. and *Midgley, P.M.* 1993: Production and release to the atmosphere of chlorodifluoromethane (HCFC-22). *Atmospheric Environment 27,* 2215-2223.

Gamlen, P.H., Lane, B.C., Midgley, P.M. and *Steed, J.M.*, 1986: The production and release to the atmosphere of CCl_3F and CCl_2F_2 (chlorofluorocarbons CFC 11 and CFC 12). *Atm. Environ. 20,* 1077-1085.

Hammitt, J.K., Camm, F., Connell, P.S., Mooz, W.E., Wolf, K.A., Wuebbles, D.J. and *Bamezai, A.*, 1987: Future emission scenarios for chemicals that may deplete stratospheric ozone. *Nature 330,* 771-716.

Houghton, J.T., Callander, B.A. and *Varney, S.K.*, (eds.) 1992: *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment.* Published for the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC, 1994*: Radiative forcing of climate change. The 1994 report of the scientific assessment working group of IPCC. Summary for policy makers.* Intergovernmental Panel on Climate Change.

Ko, M.K.W., Sze, N.D., Wang, W.C., Shia, G., Goldman, G., Murcray, F.J., Murcray, D.G. and *Rinsland, C.P., 1993*: Atmospheric sulphur hexafluoride: sources, sinks and greenhouse warming. *J. Geophys. Res. 98 (D6),* 10499-10507.

Kroeze, C. and *Reijnders, L.*, 1992: Halocarbons and global warming II and III. *Science of the Total Environment 112,* 269-314.

Kroeze, C., 1994: *Potential Effect of HFC Policy on Global Greenhouse Gas Emissions in 2035. RIVM Report no. 773001002.* National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Kroeze, C., 1995: *Fluorocarbons and SF_6. Global Emission Inventory and Options for Control. RIVM Report no.* 773001007. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

McCarthy, R.L., Bower, F.A., and *Jesson, J.P.*, 1977: The fluorocarbon-ozone theory-I. Production and release-world production and release of CCl_3F and CCl_2F_2 (fluorocarbons 11 and 12) through 1975. *Atmospheric Environment 11,* 491-497.

McCulloch, A., 1992: Global production and emissions of bromochlorofluorodifluoromethane and bromotrifluoromethane (Halons 1211 and 1301). *Atmos. Environ.* 26, 1325-1329.

McCulloch, A., 1994a: Sources of hydrochlorofluorocarbons, hydrofluorocarbons and fluorocarbons and their potential emissions during the next twenty five years. *Environmental Monitoring and Assessment 31,* 167V1-74.

McCulloch, A., 1994b: *Sources of Hydrochlorofluorocarbons, Hydrofluorocarbons, and Fluorocarbons and their Potential Emissions during the Next Twenty Five Years.* Maastricht.

Midgley, P.M. and *Fisher, D.A.*, 1993: The Production and release to the atmosphere of CFCs 113, 114 and 115. *Atmos. Environ.* 27, 271-276.

Pepper, W., Leggett, J., Swart, R., Wasson, J., Edmonds, J., and *Mintzer, I.*, 1992: *Emission scenarios for the IPCC. An update.*

UNEP, 1987: *The Montreal Protocol on Substances that Deplete the Ozone Layer. Final Act, Na.87-6106.* United Nations Environmental Programme (UNEP), Ozone secretariat, Nairobi, Kenya.

UNEP, 1991: Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer. Second edition. United Nations Environmental Programme (UNEP), Ozone secretariat, Nairobi, Kenya.

UNEP, 1992: *Report of the Fourth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer.* Na. 92-6155. United Nations Environmental Programme (UNEP), Ozone secretariat, Nairobi, Kenya.

UNEP, 1994: *Montreal Protocol on Substances that Deplete the Ozone Layer. 1994 Report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee.* United Nations Environmental Programme (UNEP), Nairobi, Kenya.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Comparison of Inventory Methods for Estimating National Emissions of Nitrous Oxide (N_2O)

Carolien Kroeze

Wageningen Institute for Environment and Climate Studies, Agricultural University, P.O. Box 9101, 6700 HB Wageningen, The Netherlands
Research performed at the National Institute of Public Health and Environmental Protection, P.O. Box 1, 3720 BA Bilthoven, The Netherlands

Abstract—This paper describes two methods to estimate country emissions of nitrous oxide. The two methods are used to calculate Dutch 1990 emissions. The first method (IPCC method) follows the IPCC Guidelines developed by IPCC/OECD. When applied to the Netherlands, the IPCC method results in 1990 emissions of 17 (6–38) Gg Ny^{-1}. Abiogenic emissions from industry and transport are the most important emissions in the Netherlands in this method. The second method (NEO method) is an update of an existing RIVM methodology, resulting in considerably higher emissions for 1990 than the IPCC method: 37 (13–70) Gg N y^{-1}, with a major contribution from agriculture.

The IPCC and NEO methods differ with respect to (i) the number of sources included, and (ii) the emission factors used. First, the NEO method includes more sources than the IPCC method, because an IPCC method has not been described yet for emissions as a result of nitrogen leaching from soils, other nitrogen loading in surface waters, wastewater treatment, atmospheric deposition of NO_x and nonagricultural NH_3, manure in stables, atmospheric formation, and use in anaesthesia. Second, for some sources the NEO method uses region-specific emission factors, which have been validated with Dutch research.

According to the NEO method, at least 95 percent of the Dutch 1990 emissions are anthropogenic. About half of the emissions are from agriculture, about one third from industry, and 10 percent from transport. Most of the agricultural emissions are from soils (about 85 percent), while surface waters (leaching) and animal manure in stables contribute about 15 percent.

Key-words: nitrous oxide (N_2O), national emissions, the Netherlands.

1. Introduction

Nitrous oxide (N_2O) is one of the greenhouse gases of which atmospheric concentrations have been increasing. The potential risks of climate change were recognized in the United Nations Framework Convention on Climate Change (FCCC) in June 1992 at the Earth Summit in Rio de Janeiro. Countries that signed the convention committed themselves, among other things, to submit information about the quantities of greenhouse gases that they emit, by source, and their national sinks.

The IPCC (Intergovernmental Panel on Climate Change) *Guidelines for National Greenhouse Gas Inventories*, internationally applicable default methods, are being developed by *IPCC/OECD* (1995). The method for N_2O has been proposed at an international IPCC workshop (*Van Amstel,* 1993). This method will hereafter be referred to as the 'IPCC method'.

In the Netherlands, an alternative method for estimating Dutch N_2O emissions has been developed (*Kroeze,* 1994). This method, referred to hereafter as the 'NEO method', is an update of the RIVM inventory for *National Environmental Outlook 3* (*RIVM,* 1993a; *Van Amstel et al.,* 1994).

The purpose of this paper is to compare the IPCC and NEO methods in order to investigate the differences. Formulating guidelines for national emission inventories is a continuous process, to which this comparison may contribute.

2. The IPCC Method

The IPCC method is an internationally applicable default method, under development, to quantify national anthropogenic N_2O emissions (*Box 1*). The draft method used here is described in *IPCC/OECD* (1995) on the basis of the results of an international workshop (*Mosier* and *Bouwman,* 1993; *Olivier,* 1993b).

Box 1. The IPCC method

Energy: stationary combustion

N_2O Emission from stationary sources (g N_2O y^{-1}) = S(EF_{abcd} × $Quantity_{abcd}$), where

EF	= emission factor (g N_2O GJ^{-1})
Quantity	= fuel input (GJ y^{-1})
a	= fuel type
b	= sector type
c	= technology type
d	= activity

Energy: mobile combustion

N_2O emissions from mobile combustion (g N_2O y^{-1}) = S(EF_{abcd} × $Quantity_{abcd}$), where

EF	= emission factor (g N_2O GJ^{-1} or g N_2O km^{-1})
Quantity	= amount of energy consumed (GJ y^{-1}) or distance travelled (km y^{-1}) × mean fuel consumption
a	= transport mode (road, rail, air, water)
b	= fuel type (diesel, gasoline, LPG, jet fuel, etc.)
c	= vehicle type (passenger cas, light duty truck, heavy duty truck, bus)
d	= emission controls and other factors

Industry

N_2O emissions from industrial sources (g N_2O y^{-1}) = S($Activity_{ij}$ × EF_{ij}), where

EF	= effective emission factor (g N_2O per kg product = kg N_2O per ton product) = = EF_j × abatement $factor_j$
Activity	= production level (ton of adipic acid or nitric acid produced)
i	= total activity type
j	= part of activities of type i with a specific applicable abatement factor
Abatement factor	= 1 - percentage abated/100

Agriculture

N_2O emissions from agricultural soils (g N_2O y^{-1}) = S(F_{mn} + F_{on} + F_{bnf})*C, where

F_{mn}	= amount of nitrogen fertilizer applied (g N y^{-1})
F_{on}	= amount of organic nitrogen applied (animal manure or crop residue) (g N y^{-1})
F_{bnf}	= amount of biological nitrogen fixation (g N y^{-1})
C	= emission coefficient: 0.0040 (0.0015 - 0.0171) g N_2O per g N, or 0.0026 (0.0010 - 0.0109) g N_2O-N per g N, based on the 1990 global mix of nitrogen fertilizers used (*Bouwman*, personal communication); differs from the coefficients presented in *Mosier* and *Bouwman* (1993).

N_2O emissions from burning of savannas and agricultural wastes

The method relies on estimation of the gross CO_2 flux based on the amount of C in the biomass (the C/N ratio), and the efficiency of the burning. N_2O emissions are estimated as a ratio to nitrogen emitted.

3. The NEO Method

The NEO method, described in *Kroeze* (1994), is an update of the Dutch National Environmental Outlook 3 (*RIVM,* 1993a, b). The NEO method distinguishes biogenic (of biological origin) and abiogenic emissions (*Box 2*). In the following discussion, first three types of biogenic emissions are described: natural emissions (3.1), enhanced background emissions, (3.2) and emissions induced by anthropogenic input of nitrogen (3.3). Next, abiogenic emissions are described. These are natural (3.4) or anthropogenic (3.5).

Box 2. The NEO method

$$N_2O_{total} = N_2O_{biogenic} + N_2O_{abiogenic}$$

$$N_2O_{biogenic} = N_2O_{biogenic,\ natural} + N_2O_{anthropogenic\ backround} + N_2O_{N\ input}$$

$$N_2O_{anthropogenic\ background} = N_2O_{current\ background} - N_2O_{biogenic,\ natural}$$

$$N_2O_{N\ input} = \sum_{i=1}^{m} (N\ INPUT)_i \times EF_i$$

$$N_2O_{abiogenic} = N_2O_{abiogenic,\ natural} + N_2O_{abiogenic,\ anthropogenic}$$

where

N_2O_{total}	= total N_2O emission (Gg N y^{-1})
$N_2O_{biogenic}$	= biogenically produced N_2O (Gg N y^{-1})
$N_2O_{abiogenic}$	= abiogenically produced N_2O (Gg N y^{-1})
$N_2O_{abiogenic,\ natural}$	= natural part of abiogenically produced N_2O (Gg N y^{-1})
$N_2O_{abiogenic,\ anthropogenic}$	= anthropogenic part of abiogenically produced N_2O (Gg N y^{-1})
$N_2O_{biogenic,\ natural}$	= natural part of biogenic background emissions (Gg N y^{-1})
$N_2O_{anthropogenic\ background}$	= anthropogenic part of biogenic background emissions (Gg N y^{-1})
$N_2O_{current\ background}$	= present-day biogenic background emissions (Gg N y^{-1})
$N_2O_{N\ input}$	= biogenic emissions induced by anthropogenic N fluxes (Gg N y^{-1})
$(N\ INPUT)_i$	= anthropogenic nitrogen flux of type i (Gg N y^{-1})
EF_i	= Emission Factor (kg N_2O-N per kg N INPUT) for a flux of type i
i	= type of N-flux or soil
m	= number of distinguished N fluxes (to soils, waters, etc.)

3.1 Natural Bogenic Emissions

Natural emissions are defined here as emissions from natural ecosystems in the preagricultural era, during which human activities had negligible impact on the land cover. Natural biogenic emissions include soil emissions and emissions from aquatic systems. For Dutch soils under the present land cover the model described by *Bouwman et al.* (1993) calculates emissions of 1.5 Gg N y^{-1} (*Bouwman* and *Van der Hoek,* 1991). Although the present land cover in the Netherlands is largely anthropogenic, the calculated flux may be considered the natural part of biogenic N_2O emissions from soils, because the model does not take into account emissions induced by anthropogenic nitrogen enrichment. The uncertainty range of this flux is tentatively set at minus 50 percent to +100 percent. In the NEO method it is therefore assumed that natural, biogenic soil emissions in the Netherlands equal 1.5 (0.5–3.0) Gg N y^{-1}. Natural emissions from aquatic systems cannot be quantified at present.

3.2 Enhanced Background Emissions

Background emissions are defined as the fluxes of N_2O from fields that have not been fertilized for at least one growing season. Current background emissions may be higher than historic natural emissions, because of the conversion of natural ecosystems to agriculture, changes in the hydrology, or effects of long-term fertilizer use. In the NEO method it is assumed that current backgroup emissions are 10 (1–20) kg N ha^{-1} y^{-1} for grassland on organic soils. This rate has been estimated from observed fluxes in and outside the Netherlands (*Bouwman* and *Van der Hoek,* 1991; *Velthof* and *Oenema*, 1994a). The emission factors for grassland on mineral soils and arable land are set at 1 (0.5–5) kg N ha^{-1} y^{-1}, based on an analysis of *Bouwman* (1994). Using these emission factors, the current background emissions from Dutch organic and mineral soils are calculated to be 4.5 (1.1–14.1) Gg N y^{-1}. As the natural part is 1.5 Gg N y^{-1} (see above), the anthropogenic increase is 3.0 Gg N y^{-1}. For aquatic systems the increased background emission is assumed to be negligible.

3.3 Emissions Induced by Annual Nitrogen (N) Inputs

Inputs of N to soils and aquatic systems directly enhance biogenic N_2O production. In the NEO method, the resulting N_2O emissions are calculated as a percentage of the N input. Four classes of emission factors are used (*Table 1*). Class 2 (0.2–1.25 percent) is closest to the range used in the IPCC method (0.1–1.1 percent). For some nitrogen fluxes N_2O emissions may be less than 0.2 percent (class 1), or more than 1.25 percent (class 3 and 4). The N inputs considered are (i) synthetic nitrogen fertilizer, (ii) animal manure, (iii) atmospheric deposition of NO_x and NH_x, (iv) biological N2 fixation, (v) nitrogen loading to surface waters, (vi) sewage treatment, and (vii) landfills.

Table 1. The NEO method emission factors for biogenic N_2O emissions induced by N input

Emission factor class	N INPUT[2]	Contributing sector
Class 1: <0.2% of N flux	- anaerobic storage of liquid and solid manure	agriculture
Class 2: 0.2–1.25% of N flux	- synthetic fertilizer on mineral soil[1]	agriculture
	- surface application of manure as fertilizer on mineral soil[1]	agriculture
		agriculture
	- faeces produced in meadow[1]	agriculture/energy
	- atmospheric deposition of NO_x and NH_3	agriculture
	- biological N_2 fixation (legumes)	agriculture
	- nitrogen leaching/run-off	industry/waste/energy
	- other nitrogen loading surface waters	waste
	- landfills (composting)	waste
	- nitrogen removal in sewage treatment plants	
Class 3: 1.25–2.5% of N flux	- synthetic fertilizer on organic soil[1]	agriculture
	- surface application of manure as fertilizer on organic soil[1]	agriculture
		agriculture
	- injection of manure as fertilizer[1]	agriculture
	- urine patches[1]	agriculture
	- biological treatment of veal calf manure	
Class 4: >2.5% of N flux	- nitric acid (HNO_3-N) added to manure[3]	agriculture
	- deep litter stable or other aerobic storage of manure[1]	agriculture

[1] Excluding NH_3-N emissions; [2] Anthropogenic N flux to soils, waters, etc.; [3] Additional emissions of N_2O induced by HNO_3-N; to be added to the manure-N induced emissions

(i) Synthetic nitrogen fertilizer

In the NEO method classes 2 and 3 are used for synthetic nitrogen fertilizers (Table 1). This range is based on *Bouwman* (1994), who concluded that 1.25 (0.25–2.25 percent) of the fertilizer N is emitted as N_2O, based on analysis of studies in which fertilizer-induced fluxes of N_2O were measured for a full year. The range is also in agreement with estimates by Mosier, as published in the IPCC Guidelines *(IPCC/OECD,* 1995*)*. The large spatial and temporal variation in soil emissions makes it difficult to identify conditions with higher or lower emissions. Nevertheless, the NEO method assumes that emissions from organic soils are higher than emissions from mineral soils. *Velthof* and *Oenema* (1994a) observed that in grasslands on mineral soils 1 percent, and on organic soils 2–4 percent of the fertilizer N was emitted as N_2O. In the NEO method, therefore, class 2 is used for surface application of fertilizers on mineral soils, and class 3 for organic soils (Table 1). The effect of the type of fertilizer on N_2O is yet too uncertain to use (*Mosier,* 1993, 1994; *Bouwman,* 1994).

(ii) Animal manure

Manure-induced N_2O emissions can take place in meadows, in stables, and after the use of manure as fertilizer.

— *Urine patches and feces in meadows.* The NEO method uses class 3 for urine (1.25–2.5 percent) and class 2 for feces (0.2–1.25 percent) produced in meadows (Table 1). Several studies indicate that the N_2O flux from urine patches in grazed grasslands may exceed class 2 (*Velthof* and *Oenema,* 1994a and 1994b; *De Klein,* 1994; *Van Faassen,* personal communication; *Slanina et al.,* in prep.). Urine patches can show high emissions of N_2O, because of the high concentrations of NH_4^+, increased moisture content, and high pH (*Van Faassen,* 1993). The N_2O emissions induced by feces-N are less well known, but they are probably lower than those induced by urine N because the NH_4^+ content of feces is low.

— *Stables.* Emissions of N_2O from stables depend on prevailing conditions. Liquid and most solid manure become anoxic during storage. This may result in low N_2O emissions, because during permanent anaerobiosis nitrification is inhibited (*Oenema et al.,* 1993) and denitrification is low. Therefore, class 1 (less than 0.2 percent) is used in the NEO method for the anaerobic storage of manure. There are three situations with higher N_2O emissions: deep litter stables, the addition of nitric acid, and the biological treatment of manure. Class 4 (greater than 2.5 percent) emission factors are used for manure in deep litter stables (based on *Groenesteijn et al.,* 1993) and nitric acid added to manure (based on *Oenema* and *Velthof,* 1993, and *Velthof* and *Oenema,* 1993). Both have been proposed as possible measures to reduce NH_3 emissions. Class 3 emission factors (1.25–2.5 percent) are used for biologically-treated manure. In the Netherlands, almost all veal calf manure is biologically treated. During this process, about 95 percent of the nitrogen is removed by nitrification and denitrification (*Willers et al.,* 1993), and related N_2O emissions may exceed class 2.

— *Manure used as fertilizer.* In general, N_2O soil emissions caused by the surface application of manure are within the same range as those caused by synthetic fertilizers (*Bouwman,* 1994). Therefore, class 2 is used for surface application of manure on mineral soils and class 3 for organic soils. In addition, the NEO method assumes that injection gives rise to higher N_2O emissions than surface application. Observations show that injection of the synthetic fertilizer anhydrous NH_3 causes higher emissions than surface application of fertilizers, and that N_2O emissions increase with injection depth (*Breitenbeck* and *Bremner,* 1986a, b). Increased denitrification or increased N_2O emissions as a result of injection of manure has been observed by *Thompson et al.* (1987), *Comfort et al.* (1990), and *Petersen* (1992). After injection of manure, the locally high levels of mineral nitrogen may result in incomplete nitrification and denitrification, leading to high production of N_2O. The NEO method therefore uses class 3 for manure injected or otherwise placed *in* the soil (Table 1).

(iii) N_2O emissions induced by atmospheric deposition of NO_x and NH_x

Atmospheric deposition of nitrate (NO_3^-) and ammonium (NH_4^+) may increase biogenic N_2O production in soils and waters. In the NEO method, N_2O emissions induced by atmospheric deposition are estimated as 0.2–1.25 percent (Class 2) of the NO_x-N and NH_3-N *emissions* in the Netherlands. Thus all N_2O induced by Dutch emissions of NO_x and NH_3 are assigned to the Netherlands, regardless in what country the N_2O is formed. Likewise, nitrous oxide resulting from deposition in the Netherlands of NO_x and NH_3 from other countries is not included. Class 2 emission factors are used, because atmospheric deposition of nitrate and ammonium can be regarded as a surface application of synthetic nitrogen fertilizer on agricultural soils. Class 2 is in agreement with observed fluxes outside the Netherlands (*Bowden et al.*, 1991; *Brumme* and *Beese*, 1992).

(iv) Biological N_2 fixation

Legumes live in symbiosis with bacteria, which are able to use atmospheric N_2 as a source of nitrogen. Since legumes increase the mineral nitrogen content of soils, they may stimulate N_2O production. However, their effects on nitrous oxide emissions have not been extensively studied. Class 2 emission factors are used in the NEO method, based on *IPCC/OECD* (1995).

(v) Leaching and run-off; nitrogen loading to surface waters

Nitrogen inputs to surface waters may enhance biogenic production of N_2O. One of the most important sources of nitrogen in Dutch surface waters is N leaching from agricultural soils. Other sources of N are sewage and industries. About 50 percent of the N input to estuaries is denitrified (*Seitzinger*, 1990) and in general less than 0.5 percent of denitrified N is emitted as N_2O, although from heavily polluted sediments N_2O emissions may be as high as 6 percent (*Seitzinger*, 1988). If this also holds for Dutch rivers, it is unlikely that N_2O emissions from surface waters exceed 1.25 percent of the N input, except when the N loading is extremely high. Therefore, the NEO method uses class 2 emission factors for Dutch N inputs to surface waters.

(vi) Sewage treatment plants

The NEO method uses class 2 (0.2–1.25 percent of N removal) for sewage treatment plants, based mainly on *BKH* (1994). Nitrogen enters sewage treatment plants mostly as NH_4^+. In sewage treatment plants, N_2O can be produced during both nitrification and denitrification. Denitrification may be the most important (*Debruyn et al.,* 1994). Reported N_2O emissions range from 0.1 to 6 percent of the N in influent (*Nogita et al.,* 1981; *BKH,* 1994), or up to 11 percent of the denitrified N (*Hong et al.,* 1993).

(vii) Landfills and organic wastes

The N_2O production in landfills is poorly known. Organic waste in landfills may be considered an N input into soils. Because no studies are available on this source, class 2 could be tentatively used.

3.4 Natural Abiogenic Emissions

Abiogenic N_2O formation occurs in the troposphere and soils. Abiogenic N_2O formation in soils (chemodenitrification) is often biologically induced, and therefore included in biogenic emissions. Three mechanisms of N_2O formation in the troposphere are described in the literature (see *Kroeze,* 1994), but only for one of these mechanisms has the source strength been quantified. *Dentener* (1993) calculated that globally 1.3 percent of the nitrogen emitted as NH_3 is oxidized to N_2O. At mid-latitudes this percentage is lower as a result of lower OH concentrations. For the grid cell covering the Netherlands, the model calculates N_2O production equaling 0.01 (0–0.05) percent of the NH_3-N emissions (*Dentener*, personal communication). It is assumed that 10 percent of this amount is natural and 90 percent anthropogenic (*Table 2*).

3.5 Anthropogenic Abiogenic Emission

Nitrous oxide can be formed abiogenically in combustion processes, industries, and in polluted atmosphere.

- *Stationary combustion.* The NEO method adopts the IPCC emission factors for stationary combustion (Table 2). The only exception is the emission factor for Fluidized Bed Combustion (FBC), which is taken from *Spoelstra* (1993). The IPCC emission factors are from *De Soete* (1993), based on measurements in about 95 power plants outside the Netherlands. A limited number of observations indicates, that in the Netherlands, N_2O concentrations in power plant exhaust gases may be at the lower end of the range observed by *De Soete* (1993) (*Spoelstra,* 1993).
- *Mobile combustion.* For mobile combustion, the emission factors of *Baas* (1991) are used in the NEO method, because these are based on data from typical European vehicles. The IPCC emission factors, on the other hand, are largely based on data from the USA. In the USA cars and driving behavior are different from those in Europe, which affects the formation of N_2O. New measurements by *Baas* (1994) generally confirm the ranges used here.

Table 2. The NEO method emission factors for abiogenic processes

	NEO method emission factor[1]	Remark
Natural emissions		
- atmospheric formation	0.001 (<0.005)% g NH_3-N emitted	*Dentener* (personal communication)
Anthropogenic emissions		
Energy: stationary combustion		
- gas	0.064 (0–0.700) g N_2O-N GJ^{-1}	as the IPCC method
- oil	0.382 (0-1.782) g N_2O-N GJ^{-1}	as the IPCC method
- coal; non-FBC	0.891 (0-6.364) g N_2O-N GJ^{-1}	as the IPCC method
- coal; FBC	26.7 (4.4 - 49) g N_2O-N GJ^{-1}	*Spoelstra* (1993)
Energy: mobile combustion		
passenger vehicles:		
- gasoline no control	0.015 (0.004–0.060) g N_2O km^{-1}	*Baas* (1991)
- gasoline new 3-way catalyst	0.035 (0.020–0.250) g N_2O km^{-1}	
- gasoline old 3-way catalyst	0.120 (0.110–0.320) g N_2O km^{-1}	
- diesel	0.031 (0.030–0.040) g N_2O km^{-1}	
freight:		
- low duty gasoline	0.045 (0.004–0.060)[2] g N_2O km^{-1}	
- heavy duty diesel	0.200 (0.029–0.840) g N_2O km^{-1}	
Industry		
- nitric acid production	17 (7–27) g N_2O–N per kg HNO_3–N	as the IPCC method
- adipic acid production	191 g N_2O–N per kg adipic acid	as the IPCC method
- other chemical industry	1.1 Gg N_2O–N y^{-1}	*VROM* (1993)
Waste		
- municipal solid waste incineration	12.7 (3.2–127) g N_2O–N per ton	*Spoelstra* (1993) and IPCC method
Other		
- atmospheric formation	0.009 (<0.045)% g NH_3-N emitted	*Dentener* (personal communication)
- anaesthesia	use = emission	

[1] In g N_2O-N per activity; for mobile combustion in g N_2O per activity (1 g N_2O = 28/44 g N);
[2] Range as passenger vehicles (gasoline without catalyst)

— *Industry*. The IPCC emission factors for nitric acid and adipic acid production are also used in the NEO method. The emission factors for nitric acid are based on measurements in plants outside the Netherlands (*De Soete*, 1993). Measurements of N_2O in Dutch nitric acid plants may become available in 1995 and 1996 (for example, *HAS*, 1994; *Van Der Meer*, personal communication).

Emissions of 1.1 Gg N_2O-N y^{-1} from other chemical industries have been reported to the Dutch emission registration, but the exact origin of the source needs further research (*RIVM,* 1993a; *VROM,* 1993).

- *Municipal waste incineration.* The NEO emission factor for waste incineration (12.7 g N_2O-N per ton) is based on measurements in Dutch incinerators (*Spoelstra,* 1993). The upper limit of the range (127 g N_2O-N per ton) is taken from the IPCC method, and the lower limit (3.2 g N_2O-N per ton) is from recent measurements in two Dutch incinerators (*Oonk,* unpublished results).
- *Atmospheric formation.* As described for abiogenic natural emissions, N_2O formation is estimated as 0.01 (0–0.05)% of the NH_3–N emitted, of which 90 percent is anthropogenic (*Dentener,* personal communication).
- *Anaesthesia.* It is assumed here that annual emissions equal the medical use of nitrous oxide.

4. Dutch 1990 Emissions

The IPCC method results in considerably lower emissions than the NEO method (*Table 3*; *Fig. 1*). The Dutch anthropogenic N_2O emissions based on the IPCC method amount to 17.3 (6.3–38.0) Gg N y^{-1}, of which at least half are industrial. The emission calculated with the NEO method is 37.1 (13.0–69.7) Gg N y^{-1}, of which more than 95 percent is anthropogenic, and more than half biogenic. There are two reasons for these differences:

4.1 Number of Sources Included

The NEO method identifies more sources of N_2O than the IPCC method. The following sources of N_2O are not included in the IPCC method: natural emissions, emissions induced by atmospheric deposition of NO_x and non-agricultural NH_3, other chemical industries, background emissions from soils, emissions from stables, N leaching, sewage treatment, atmospheric formation, N input to surface waters, and medical use. Nitrous oxide emissions from these sources are 11 Gg N y^{-1}. These additional sources explain about 55 percent of the difference in total emissions between the two methods (Table 3).

4.2 Emission Factors Used

The emission factors used in the methods differ. The NEO emission factors are higher for soil emissions, and lower for traffic and waste incineration than the IPCC factors. As a result, soil emissions induced by N inputs are about 9 Gg higher in the NEO method than in the IPCC method (Table 3). Higher emission factors for soils may be realistic, because in the Netherlands nitrogen inputs are

Table 3. Dutch 1990 emissions of N_2O (in Gg N y^{-1}): a comparison between the IPCC method and the NEO method; n.q. not quantified, because not included in the method

Source	IPCC method	NEO method	Difference NEO-IPCC	Remarks
Natural emissions				
- soils	n.q.	1.5	1.5	not included in IPCC method
- aquatic sources	n.q.	n.q.	n.q.	not included in IPCC/NEO method
- atmospheric formation	n.q.	<0.1	<0.1	not included in IPCC method
Total	n.q.	1.5	1.5	
Anthropogenic emissions				
Energy				
- stationary sources	0.6	0.7	<0.1	methods use different emission factors
- mobile sources	3.7	3.4	-0.3	methods use different emission factors
- NO_x emissions	n.q.	1.2	1.2	not included in IPCC method
Industry				
- adipic acid	0.0	0.0	0.0	IPCC method = NEO method
- nitric acid	10.5	10.5	0.0	IPCC method = NEO method
- other chemical industry	n.q.	1.1	1.1	not included in IPCC method
Agriculture				
- enhanced background emissions	n.q.	3.0	3.0	not included in IPCC method
- fertilizer	1.1	4.4	3.4	methods use different emission factors
- manure in stables	n.q.	0.5	0.5	not included in IPCC method
- manure applied as fertilizer[1]	1.3	5.4	4.1	methods use different emission factors
- NH_3 emissions	n.q.	1.6	1.6	methods use different emission factors
- N_2 fixation	<0.1	0.2	0.1	methods use different emission factors
- leaching/run-off	n.q.	1.8	1.8	not included in IPCC method
Waste				
- waste incineration	<0.1	<0.1	-0.0	not included in IPCC method
- sewage treatment	n.q.	0.3	0.3	not included in IPCC method
Other				
- atmospheric formation	n.q.	<0.1	<0.1	not included in IPCC method
- non-agricultural N-load waters	n.q.	0.6	0.6	not included in IPCC method
- non-agricultural NH_3 emissions	n.q.	0.1	0.1	not included in IPCC method
- non-energy NO_x emissions	n.q.	0.5	0.5	not included in IPCC method
- anaesthesia	n.q.	0.3	0.3	not included in IPCC method
- global warming	n.q.	0.0	0.0	not included in IPCC method
Total	17.3	35.6	18.3	
Natural + anthropogenic	**17.3**	**37.1**	**19.8**[2]	

[1] This includes manure produced in meadows;
[2] 11 Gb because sources are not included in the IPCC method and 9 Gg because of different emission factor used;

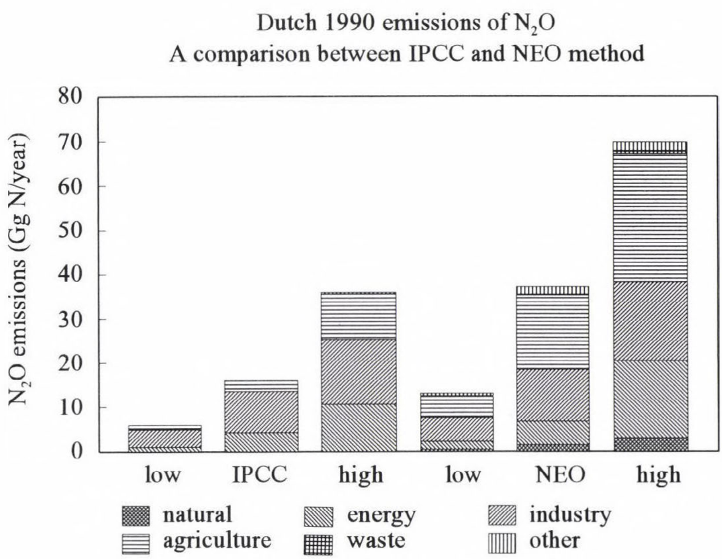


Fig. 1. Dutch 1990 emissions, including a low and a high estimate, according to the IPCC method (based on the IPCC Guidelines for National Greenhouse Gas Inventories) and the NEO method (update of Dutch *National Environmental Outlook 3*).

excessive, which may result in higher percentage emissions. On the other hand, the IPCC method may underestimate fertilizer-induced emissions, because the IPCC emission factors are derived from studies in which N_2O fluxes were measured for less than a year (*Eichner*, 1990); the IPCC emission factors are not corrected for N_2O produced outside the sampling period. For road vehicles the emission factors of *Baas* (1991) are used in the NEO method, resulting in 3.4 Gg N y^{-1}, which is somewhat lower than the 3.7 Gg of the IPCC method. Also N_2O emissions from waste incineration are slightly lower in the NEO method. The net effect of different emission factors explains about 45 percent (9 Gg N y^{-1}) of the difference between the IPCC and NEO method (Table 3).

Fig. 1 shows that there is little overlap in the uncertainty ranges of the two methodologies. This illustrates the uncertainties that still exist about emissions of N_2O. Some sources are difficult to quantify because of the limited number of measurements available (for example, Dutch industrial sources), while others show large spatial and temporal variability that makes extrapolation of observations difficult (for example, biogenic sources). Nevertheless, knowledge about a number of nitrous oxide emissions has increased. There is little doubt that additions of nitrogen to soils or surface waters in whatever form, result in emissions of N_2O. Similarly, it is clear that combustion processes are a source of N_2O, and that catalysts in cars tend to increase emissions from mobile combustion. Despite the large spatial and temporal variability of the fluxes, it is possible to define ranges of emission factors.

5. *Conclusion*

Two methods are described to estimate N_2O emissions from the Netherlands. The IPCC method is the calculation scheme proposed during an IPCC workshop as a default method for national inventories (*Van Amstel,* 1993). The NEO method, described in *Kroeze* (1994) is an update of the RIVM method used in *National Environmental Outlook 3* (RIVM, 1993a, b).

There are considerable differences between the two methods. Dutch emissions amount to 17.3 (6.3–38.0) Gg N y^{-1} using the IPCC method and 37.1 (13.0–69.7) Gg N y^{-1} for the NEO method. The difference has two major causes: the NEO method includes more sources than the IPCC method, and the two methods use different emission factors.

At present more than 95 percent of the Dutch N_2O emissions are anthropogenic according to the NEO method (Fig. 1). About half of the Dutch emissions stem from agricultural activities. The use of fertilizers (both synthetic and manure) is an important source of N_2O. Fertilizers, excluding manure produced in meadows, increase N_2O emissions from agricultural soils by 7.6 Gg N y^{-1}. In addition, a considerable amount of the fertilizer leaches from soils, causing N_2O emissions from, for instance, surface waters of 1.8 Gg N y^{-1}. Animal manure is an important source of NH_3, which, after atmospheric deposition, increases soil emissions of N_2O by 1.6 Gg N y^{-1}. Production of nitric acid, mainly used as feedstock for synthetic fertilizers, is an important industrial source of N_2O in the Netherlands (10.5 Gg N y^{-1}). Another important single source of N_2O in the Netherlands is transportation (3.4 Gg N y^{-1}). In particular, passenger vehicles with three-way catalytic converters appear to be an important source of N_2O, which also may increase in the near future because of catalyst aging.

Development of guidelines for national greenhouse gas inventories is a continuous process, to which country studies can contribute. The NEO method includes almost all known sources of N_2O, while the IPCC method is restricted to the most important sources on the global scale. However, the relative contribution of sources may vary regionally. It is therefore recommended here to include the following anthropogenic sources in the IPCC guidelines: emissions induced by atmospheric deposition of NO_x and nonagricultural NH_3, other chemical industries, background emissions from soils, emissions from stables, N leaching, sewage treatment, atmospheric formation, N input to surface waters, and medical use.

Acknowledgements—This study was performed at the National Institute of Public Health and Environmental Protection in the Netherlands, and commissioned by the Air and Energy Directorate of the Directorate-General for Environmental Protection of the Dutch Ministry of Housing, Physical

Planning and Environment (project 773001; RIVM report no. 773001004; project leaders *R.A.W. Albers* and *R.J. Swart*). The author gratefully acknowledges *A.F. Bouwman, K.W. Van der Hoek,* and *J. Oonk* for their contributions to the study.

References

Baas J., 1991: *Literature Research Regarding Laughing Gas Emissions by Road Traffic* (in Dutch). TNO Report R 91/322. TNO-IMW, Delft, The Netherlands.

Baas J., 1994: *Nitrous oxide emissions from road transport in the Netherlands.* TNO Report R 94/208. TNO Institute of Environmental Sciences. Delft, The Netherlands.

BKH, 1994: *Study Regarding the Creation of N_2O in Purification Plants* (in Dutch). Literature research and preliminary measurements. BKH Report RO181018/23501/2. Delft, The Netherlands.

Bouwman, A.F., 1994: *Method to Estimate Direct Nitrous Oxide Emissions from Agricultural Soils.* RIVM report no. 773004004. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Bouwman, A.F. and *Van der Hoek, K.W.*, 1991: *Analysis of Soil and Water Borne Emissions of Nitrous Oxide and Methane in the Netherlands.* RIVM report no. 736301010. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Bouwman, A.F., Fung, I., Matthews, E. and *John, J.*, 1993: Global analysis of the potential for N_2O production in natural soils. *Global Biogeochem. Cycles 7,* 557–597.

Bowden, R.D., Melillo, J.M. and *Steudler, P.A.*, 1991: Effects of nitrogen additions on annual nitrous oxide fluxes from temperate forest soils in the northeastern United States. *J. Geophys. Res. 96,* 9321–9328.

Breitenbeck, G.A. and *Bremner, J.M.*, 1986a: Effects of various nitrogen fertilizers on emissions of nitrous oxide from soils. *Boil. Fertil. Soils 2,* 195–199.

Breitenbeck, G.A. and *Bremner, J.M.*, 1986b: Effects of rate and depth of fertilizer application on emissions of nitrous oxide from soil fertilized with anhydrous ammonia. *Biol. Fertil. Soils 2,* 201–204.

Brumme, R. and *Beese, F.*, 1992: Effects of liming and nitrogen fertilization on emissions of CO_2 and N_2O from a temperate forest. *J. Geophys. Res. 97,* 12851–12858.

Comfort, S.D., Kelling, K.A., Keeney, D.R. and *Converse, J.C.*, 1990: Nitrous oxide production from injected liquid dairy manure. *Soil Sci. Soc. Am. J. 54,* 421–427.

Debruyn, W., Lissens, G., Van Rensbergen, J. and *Wevers, M.*, 1994: Nitrous oxide emissions from waste water. In *J. Van Ham et al.* (eds.), 1994: 159–165.

De Klein, C.A.M., 1994: Denitrification and N_2O emission from urine-affected grassland soil in The Netherlands. In *Grassland and Society* (eds.: *L.'t Mannetje* and *J. Frame*). Proceedings of the 15th General Meeting of the European Grassland Federation, Wageningen, The Netherlands, June 1994, pp. 392–396.

Dentener, F., 1993: *Hetergeneous Chemistry in the Troposphere.* PhD Thesis. Utrecht University, The Netherlands. 179 pp.

De Soete, G.G. 1993: Nitrous oxide emissions from combustion. In *A.R. van Amstel,* 1993: 287–338.

Eichner, M.J., 1990: Nitrous oxide emissions from fertilized soils: summary of available data. *J. Environ. Qual. 19,* 272 -280.

Groenesteijn, C.M., Oosthoek, J. and *Van Faassen, H.G.*, 1993: Microbial processes in deep-litter systems for fattening pigs and emission of ammonia, nitrous oxide and nitric oxide. In *Nitrogen Flow in Pig Production and Environmental Consequences* (eds.: *M.W.A. Verstegen, L.A. den Hartog, G.J.M. van Kempem,* and *J.H.M. Metz*). Proc. of the first international symposium on nitrogen flow in pig production and environmental consequences, 8–11 June 1993. EAAP Publication no. 69. Pudoc Scientific Publishers, Wageningen, The Netherlands, pp. 307–312.

HAS, 1994: *Environmental Plans for H. A. S.* (in Dutch). September 1994, Hydro Agri Sluiskil, The Netherlands.

Hong, Z., Hanaki, K. and *Matsuo, T.*, 1993: Greenhouse gas–N_2O production during denitrification in wastewater treatment. *Water Sci. Technol. 7*, 203–207.

IPCC/OECD, 1995: *Draft Guidelines for National Greenhouse Gas Inventories.*

Kroeze, C., 1994: Nitrous oxide (N_2O). *Emission Inventory and Options for Control in the Netherlands.* RIVM report no. 773001004. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Mosier, A.R., 1993: Nitrous oxide emissions from agricultural soils. In *A.R. van Amstel*, 1993: 273–286.

Mosier, A.R., 1994: Nitrous oxide emissions from agricultural soils. *Fertilizer Res. 37*, 191–200.

Mosier, A.R. and *Bouwman, A.F.*, 1993: Working group report: nitrous oxide emissions from agricultural soils. In *A.R. van Amstel*, 1993: 343–346.

Nogita, S., Saito, Y. and *Kuge, T.*, 1981: A new indicator of the activated sludge process – nitrous oxide. *Water Sci. Technol. 13*, 199–204.

Oenema, O. and *Velthof, G.L.*, 1993: Denitrification and nitric-acid-treated slurry during storage. *Neth. J. Agric. Sci. 41*, 63–80.

Olivier, J.G.J., 1993a: Nitrous oxide emissions from industrial sources. In *A.R. van Amstel*, 1993: 339–342.

Olivier, J.G.J., 1993b: Working group report: nitrous oxide emissions from fuel combustion and industrial processes. In *A.R. van Amstel*, 1993: 347–357.

Petersen, S.O., 1992: Nitrification and denitrification after direct injection of liquid cattle manure. *Acta Agric. Scand., sect. B, Soil Plant Sci. 42*, 94–99.

RIVM, 1993a: *National Environmental Outlook 3.* National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

RIVM, 1993b: Environmental Efficiency of the NMP-2 (in Dutch). Aanvulling op de National Milieuverkenning 3. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Seitzinger, S.P., 1988: Denitrification in freshwater and coastal marine ecosystems: ecological and geochemical implications. *Limnol. Oceanogr. 33*, 702–724.

Seitzinger, S.P., 1990: Denitrification in aquatic sediments. In *Denitrification in Soil and Sediment* (eds.: *N.P. Revsbech* and *J. Sorensen*). Plenum Press, New York, pp. 301–312.

Slanina, J., Berdowski, J. and *Bouwman, A.F. Assessment Report of the Dutch National Research Program on Global Air Pollution and Climate Change.* Phase I, theme B (in preparation).

Spoelstra, H., 1993: *N_2O Emissions from Combustion Processes Used in the Generation of Electricity.* KEMA Report 10142-KES/MME 92-4029. KEMA Environmental Services, Arnhem, The Netherlands. 27 pp.

Thompson, R.B., Ryden, J.C. and *Lockyer, D.R.*, 1987: Fate of nitrogen in cattle slurry following surface application or injection to grassland. *J. Soil Sci. 38*, 689–700.

Van Amstel, A.R. (ed.), 1993: Proceedings of the International IPCC workshop *Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control.* Amersfoort, The Netherlands, 3–5 February 1993, National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Van Amstel, A.R., Albers, R.A.W., Kroeze, C., Matthijsen, A.C., Olivier, J.G.J. and *Spakman, J.*, 1994: *Greenhouse Gas Emissions in the Netherlands 1990, 1991, 1992 and Projections for 1990–2000. A Background Report for the National Communications of the Netherlands for the Climate Convention.* RIVM report no. 773001003. National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands.

Van Faassen, H.G., 1993: *Modeling N_2O Emissions from (grazed) Grassland. A literature review.* Nota 269. DLO-Institue for Soil Fertility, Haren, The Netherlands, 17 pp.

Velthof, G.L. and *Oenema, O.*, 1993: Nitrous oxide flux from nitric-acid-treated cattle slurry applied to grassland under semi-controlled conditions. *Neth. J. Agric. Sci. 41*, 81–93.

Velthof, G.L and *Oenema, O.*, 1994a: Nitrous oxide emissions from grassland on sand, clay and peat soils in the Netherlands. In *Non-CO_2 Greenhouse Gases: Why and How to Control?* (eds.: *J. Van Ham, L.J.H.M. Janssen* and *R.J. Swart*). Proceedings of an International Symposium, Maastricht, The Netherlands, 13–15 December 1993. Kluwer Academic Publishers, Dordrecht, The Netherlands, 439–444.

Velthof, G.L and *Oenema, O.*, 1994b: Effect of nitrogen fertilier type and urine on nitrous oxide flux from grassland in early spring. In *Grassland and Society* (eds.: *L.'t Mannetje* and *J. Frame*). Proceedings of the 15th General Meeting of the European Grassland Federation, Wageningen, The Netherlands, pp. 458–462.

VROM, 1993: *Industrial Emissions in the Netherlands. Types of Industries, Individual Species and Distribution over the Regions.* Fifth inventarisation 1990. Publication series for the registration of emissions, nr. 14. Ministry of Housing, Physical Planning and Environment, The Hague, The Netherlands.

VROM, 1994: *Netherlands' National Communication on Climate Change Policies.* Prepared for the conference of parties under the Framework Convention on Climate Change. Ministry of Housing, Physical Planning and Environment, The Hague, The Netherlands.

Willers, H.C., Ten Have, P.J.W., Derikx, P.J.L. and *Arts, M.W.*, 1993: Temperature-dependency of nitrification and required anoxic volume for denitrification in the biological treatment of veal calf manure. *Biosci. Technol. 43,* 47–52.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Specific Requirements to Methodology for Estimating of CO_2 Fluxes in Boreal and Temperate Forests

A. O. Kokorin and **I. M. Nazarov**

Institute of Global Climate and Ecology,
Glebovskaya 20b, 107258, Moscow, Russia

Abstract—Estimating carbon dioxide fluxes in boreal and in some temperate forests requires taking into consideration several important characteristics of these forests. The current paper discusses these characteristics as well as corresponding parameter values. First, several subzones of boreal taiga forests need to be separately described. The principal differences between these subzones are connected with carbon contents, tree growth and organic decomposition rates, and the possible influence of climate changes. Second, mortmass (dead biomass) is a very important carbon reservoir in boreal forests, which include parts with markedly different rates of decomposition. Third, disturbance of the internal carbon balance (caused by ageing of forests, climate factors, etc.) can be the main reason for CO_2 uptake or emissions. Yet, it is impossible to estimate balance disturbance based on total wood content data obtained in the last and the previous forest inventories. The possible solution is to assume that natural forests persist in the state of quasi-equilibrium carbon balance, that allows to use coefficients of balanced growth and decomposition to estimate emissions. Fourth, forest fires play an important role in the carbon balance of boreal forests.

Key-words: carbon dioxide, boreal forests, forest inventory, carbon balance, climate changes.

1. Introduction

The IPCC Guidelines provide the basic guidance for calculating CO_2 fluxes between forests and the atmosphere, using average values of carbon content in boreal and temperate forests (*IPCC*, 1994). In many countries, including Russia, data on forest monitoring provide sufficient information for using the IPCC methodology (*Isaev et al.*, 1993; *Handbook...*, 1995; *Bazilevich*, 1993; *Kobak*, 1988). At the same time, there are several specific characteristics of structure and processes in boreal forests that are important for CO_2 flux calculations, but not reflected in the Guidelines. The goal of this work is to describe these characteristics (using Russian forests as an example), which could be considered in the improved Guidelines.

2. Changes in Land Use

First of all, it is necessary to emphasize that in Russia statistical data on changes in land use may inadequately represent real changes. This problem was analyzed using results of the latest and the previous forest surveys (*Forest...*, 1990; *Handbook...*, 1995) and recent papers by the Federal Forestry Service and other organizations (*Strakhov et al.*, 1995). For example, comparing the total forest area from the latest and the previous surveys one can see that between 1988 and 1992 this area decreased by about 1 percent, or 8 megahectares (*Forest...*, 1990; *Handbook...*, 1995). This decrease was primarily connected with poorly described lands of the Far East and Eastern Siberia, which are managed by the Russian Federal Forestry Service (FFS). Such a decrease, which cannot be explained by cuts, fires, or other changes in land-use, resulted exclusively from more precise measurements of the same forests.

The mortmass (dead biomass) plays a very important role in carbon balance of boreal forests (*Kobak*, 1988; *Kolchugina* and *Vinson*, 1993; *Kokorin* and *Nazarov*, 1994). It is desirable to consider separately such parts of mortmass as litter and dead roots, and dead standing stems. The last part is very important in Russia, where artificial thinning of forests is not common, while decomposition rate of dry stems is significantly lower than decomposition of litter. It was shown that dry stems can store carbon for several decades (*Bazilevich*, 1993; *Kokorin* and *Nazarov*, 1994; *Shvidenko*, 1995, personal communication). The data on specific carbon contents in mature forests in Russia are given in *Table 1* (*Isaev et al.*, 1993; *Kobak*, 1988).

As one can see from Table 1, carbon content depends significantly on the natural zone. This dependence means that it is very desirable to divide data on the entire taiga forest zone into several subzones.

The decomposition processes also strongly vary from one taiga sub-zone to another (*Table 2*). Data on the decomposition of humus was taken from *Kobak* (1988); data on litter processes in the different natural zones from *Bazilevich* (1993), *Molchanov* (1977), and *Vompersky* and *Utkin* (1988); and data on green biomass and dry stems from *Bazilevich* (1993), *Molchanov* (1977), *Vompersky* and *Utkin* (1988), and *Reference book for forest taxation* (1962). The decomposition processes also include the decay of harvest residues, which may comprise up to one half of the pre-harvest phytomass content.

3. Carbon Balance Disturbance

According to forest inventory data obtained in the latest and the previous inventories in Russia (*Forest...*, 1990; *Handbook...*, 1995), changes in land-use are not significant for the majority of regions. On the other hand, the disturbance of the carbon cycle can result from different factors, for example, local climate changes, registered or non-registered cuts and fires in the past, insects,

Table 1. Specific carbon content in Russian forests, Mg C/ha

(*Atlas of the USSR,* 1986; *Atlas...,* 1973; *Bazilevich,* 1993; *Dixon* and *Krankina*, 1993; *Forest...,* 1990; *Isaev et al.,* 1993; *Kobak,* 1988; *Kokorin* and *Nazarov,* 1994 and 1995; *Molchanov*, 1977; *Vompersky* and *Utkin,* 1988)

Natural zone	Specific carbon content, Mg C/ha					
	Wood including roots[1]	Green bio-mass[1]	Dry wood of standing dead trees	Litter	Labile humus forms	Stable humus forms
Forest-tundra	30	2	6	20	50	100
North Taiga	50	3	7	18	75	150
Middle Taiga	65	4	9	15	100	200
South Taiga	80	5	9	10	100	200
North Mixed	100	3	7	6	90	180
South Mixed	120	3	5	5	80	160
Deciduous	130	3	3	4	75	150
Forest-steppe	120	3	3	4	75	150

[1] values are given for the mature forests

Table 2. Decomposition rates in Russian forests

(Vl) – litter, Vh – labile humus[1] , Vs – stable humus, Vb – green biomass and Vm – standing dead trees; (based on *Bazilevich*, 1993; *Dixon* and *Krankina*, 1993; *Kolchugina* and *Vinson*, 1993; *Kobak*, 1988; *Molchanov*, 1977; *Reference...*, 1962; *Vompersky* and *Utkin*, 1988)

Natural zona	Vl 1/yr	Vh $1/10^3$ yrs	Vs $1/10^3$ yrs	Vm 1/yr	Vb 1/yr
Forest-tundra	0.038	0.16	0.092	0.025	0.25
North Taiga	0.073	0.35	0.160	0.048	0.29
Middle Taiga	0.13	0.56	0.230	0.084	0.33
South Taiga	0.26	0.82	0.31	0.13	0.40
North Mixed	0.49	1.0	0.39	0.25	0.66
South Mixed	0.72	1.5	0.54	0.35	0.83
Deciduous	1.05	1.9	0.67	0.35	1.0
Forest-steppe	1.05	1.9	0.67	0.35	1.0

1 humification of litter: 6% from total litter decomposition, part of labile humus in humification – 60% (*Kobak*, 1988)

and so forth. Large-scale cuts lead to the increase of areas covered with young forests after a couple of years. Understanding the reasons for carbon balance disturbance requires reconstructing long-term carbon cycle dynamics (for example, starting from the pre-industrial era or from the last quarter of the 19th century in Russia). However, such investigation requires a wide variety of forest data and a corresponding simulation model that takes into account climate conditions of the last decades.

It is important to recognize that in Russia we are not able to make an accurate estimate of the total forest biomass over a large area. It means that we cannot estimate the internal balance disturbance based on total wood content data obtained in the last and the previous forest inventories.

However, this difficulty can be resolved by assuming that there was a quasi-equilibrium carbon balance in natural forests in the absence of cutting and climate change. That is, that the processes of growth, decomposition, and natural fires compensated each other completely (*Fig. 1*).

As a result, we are able to estimate the forest balance without an exact determination of all the carbon cycle links. The following two-step diagram for determining decomposition rates is proposed (Fig. 1); rates obtained by this process are presented in Table 2.

The specific feature of some subzones of boreal forests is that temperature is the strong growth-limiting factor. Moreover, temperature variations significantly influence decomposition processes. These effects were discussed in detail in our previous work (*Kokorin* and *Nazarov,* 1995). The calculation of the balance disturbance can be divided into the increment and decomposition calculations. Both processes can be influenced by climate factors. The current growth rate results from multiplying the natural growth rate by the coefficient describing the climate change influence. This coefficient is determined based on data characterizing the influence of warming, the amount of precipitation, and the atmospheric CO_2 concentration on forest growth (*Table 3*). 'Climate warming' coefficients were derived from experimental observations and literature data (*Karaban et al.,* 1993; *Kokorin* and *Nazarov,* 1994, 1995; *Kolchugina* and *Vinson,* 1993). 'Precipitation' and 'direct CO_2 effect' coefficients were taken from global carbon-cycle models (*Moiseev et al.,* 1985; *Vloedbeld* and *Leemans,* 1993).

Co-relating values from Table 3 with estimates of current and future climate variations shows that it is desirable to take into account possible climate influence, first of all, in the Middle and North Taiga and Forest-tundra. The influence of two climate factors must be considered first: (1) the warming and prolongation of growth and decomposition periods, and (2) the direct effect of atmospheric CO_2 on tree growth. It seems unlikely that changes in precipitation will have any significant impact on Russian forests, since this factor limits growth only in the forest-steppe zone. Also, current changes in precipitation are small (*Gruza et al.,* 1993).

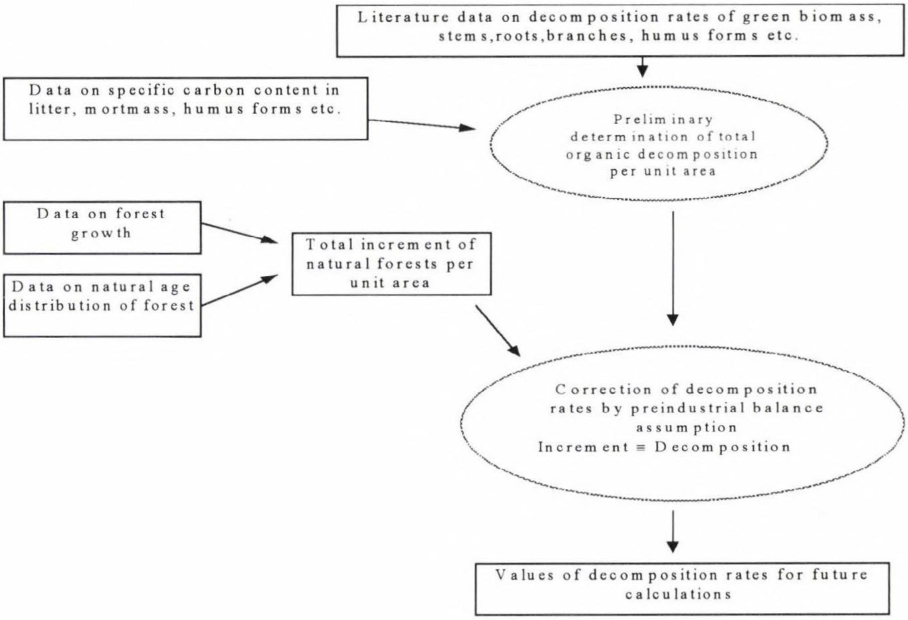


Fig. 1 Estimation of decomposition rates.

Table 3. Data on the influence of climate conditions on boreal and temperate forests (*Karaban et al.*, 1993; *Kokorin* and *Nazarov*, 1994, 1995; *Kolchugina* and *Vinson*, 1993; *Moiseev et al.*, 1985; *Vloedbeld* and *Leemans*, 1993)

Natural zone	Increase in growth rate (%)			Increase in decomposition rate per 1°C of warming (%)
	Warming by 1°C	Increase in precipitaion by 6%	Increase in CO_2 concentration by 10%	
Forest-tundra	15	-0.7	1.25	15
North Taiga	15	-0.7	1.25	13.5
Middle Taiga	12	-0.3	1.25	13.5
South Taiga	3	-2.6	0.95	12
Mixed North	8	1.0	1.0	10.5
Mixed South	3	2.8	1.25	10.5
Deciduous	3.6	4.4	1.5	9
Forest-steppe	-1.0	5.3	0.75	7.5

4. Fires

The preliminary values of parameters describing effects caused by fires in Russian forests are presented in *Table 4*.

Table 4. Average forest fire coefficients for preliminary estimations in boreal forests (*Auclair* and *Carter*, 1993; *Dixon* and *Krankina*, 1993; Furjaev, 1986; Konev, 1977).

Coefficients	Values
Natural fire probability in forests, 1/yr.	Over mature forests - 0.003 Other forests - 0.001
Part of living wood burned out in fire	0.1
Part of dry stems burned out in fire	0.7
Part of litter burned out in fire	0.2
Part of labile humus burned out in fire	0.0 - 0.2
Rate of natural reforestation of burned out places, 1/yr.	0.1 - Mixed and Decidous forests 0.03 - South Taiga 0.02 - Middle, North Taiga and Forest-Tundra

In our opinion it is necessary to adjust these values by separately considering the two main types of fires in the boreal forests:

(1) Crown fires, which are very intense and cover a relatively small part of the annually burned area (about 20 percent in Russia). These fires are catastrophic events, during which most forest biomass is destroyed.

(2) Understory fires, during which only a certain portion of trees die off. These fires cover huge areas, and it is not easy to accurately determine their boundaries.

It is necessary to emphasize that fire is an integral element of natural boreal forest growth (*Furjaev,* 1986; *Konev,* 1977). 'Natural' fires should be included in the natural carbon cycle, which, on average, is completely balanced. Unfortunately, dividing fires into 'natural' and 'man-made' is a quite complicated problem.

5. Conclusion

The following issues should be considered when estimating the CO_2 flux in boreal and some temperate forests:

- There are great differences between the carbon cycles in the different boreal forest subzones. These differences are connected to the carbon content in all carbon reservoirs and also with tree growth and organic decomposition rates.

- Mortmass is an important carbon reservoir in boreal forests. Moreover, it should be divided into two or more sub-reservoirs with different decomposition rates (for example, litter and dry standing stems).
- Data on changes in forested areas in Russia should be further analyzed by using additional information about land-use change.
- Disturbance of the internal carbon balance (caused changes in age distribution, climate factors, etc.) may be a leading factor in determining CO_2 uptake or emission rates. In Russia, it is impossible to estimate carbon balance disturbance by analyzing data on total carbon content obtained by forest surveys. This difficulty can be resolved by assuming existence of a quasi-equilibrium carbon balance in natural forests (without logging and climate impacts).
- The possible influence of local climate changes on tree growth and decomposition processes in some boreal forest subzones (Middle and North Taiga, Forest-tundra) can be very significant at present or during the next several decades. According to the available parameter values this influence may shift the carbon cycle to an additional uptake of CO_2 from the atmosphere.
- There are two main types of fires in Russian forests: crown and understory (ground) ones. The distinction between these types can play an important role in calculating CO_2 fluxes. Fire is an integral element of natural boreal forest growth. 'Natural' fires should be included in the natural carbon cycle, which on average is completely balanced.

Perhaps the discussed characteristics of Russian forests can be found in other northern regions, for example, in Scandinavia, Canada, and some parts of the United States. However, the expansion of this work requires a wide international discussion. To initiate such discussion we are preparing the prospectus of the supplemental materials to the IPCC Guidelines, which is devoted to CO_2 sinks and emissions in boreal and temperate forests.

Acknowledgements—This work was carried out in the framework of the U.S. Country Studies Program, Cooperative Agreement DE-FCO2-93PO10118 with the U.S. Dept. of Energy. The authors would like to express their gratitude to the Country Study Management Team and *Robert Dixon*, Director of the U.S. Country Studies Program for support and valuable comments.

References

Atlas of the USSR (in Russian). 1986. Moscow, GUGK. pp.260.

Atlas of Forests of the USSR (in Russian). 1973. Moscow, Goskomles. pp.222.

Auclair, A.N.D. and *Carter, T.B.*, 1993: Forest wildfires as a recent source of CO_2 at northern latitudes. *Can. J. Forest. Res. 23*, 1528-1536.

Bazilevich, N.I., 1993: *Biological Productivity of the Northern Eurasian Ecosystems* (in Russian). Moscow, Nauka. pp. 292.

Dixon, R.K. and *Krankina, O.N.*, 1993: Forest fires in Russia: carbon dioxide emissions to the atmosphere. *Can. J. Forest. Res. 23*, 700-705.

Forest Fund of the USSR (in Russian), 1990. Goskomles, Moscow. Vol. 1 and 2. pp. 1006 and 1022.

Furjaev, V.V., 1986: Reforestation-age dynamics of Pine forest under the periodical fires. In *Forest Fires and its Consequences* (in Russian). Krasnoyarsk. ILID. 83-92.

Handbook on the Forest Fund of Russia (in Russian), 1995. Federal Forestry Service, Moscow, pp. 272.

IPCC, 1994: Guidelines for National GHG Inventories. Vol. 2 and 3 (Reference Manual and Workbook).

Isaev, A.S., *Korovin, G.N.*, *Utkin, A.I.*, *Prjazhnikov, A.A.* and *Zamolodchikov, D.G.*, 1993: The estimation of carbon content and annual deposition in phytomass of Russian forest ecosystems (in Russian). *Lesovedenie*, No. 5, 3-10.

Gruza, G.V., *Rankova, E.Ya.* and *Rocheva, E.V.*, 1993: Comparison of 1931-1960 and 1961-1990 air temperature normals for the territory of the former USSR. Gruza et.al., 1993 of the 18th Annual Climate Diagnostics Workshop.1993, Boulder, NOAA USA, Nov. 1-5, 276-280.

Karaban, R.T., *Kokorin, A.O.*, *Nazarov, I.M.* and *Shvidenko, A.Z.*, 1993: CO_2 sequestration by Russian Forests (in Russian). *Meteorol. and Hydrol. Rus. J.* No. 1, 5-14.

Kobak, K.I., 1988: Biotic Components of Carbon Cycle. *Gidrometeoizdat* (in Russian), Leningrad, pp. 248.

Kokorin, A.O. and *Nazarov, I.M.*, 1994: Evaluation of the effect of climate warming and photosynthetically-active radiation on boreal forests (in Russian). *Meteorology and Hydrol. Rus. J.*, No. 5, 44-54.

Kokorin, A.O. and *Nazarov, I.M.*, 1995: The analysis of growth parameters of Russian boreal forests in warming, and its use in carbon budget model. *Ecological Modeling* (in press) pp. 12.

Kolchugina, T.P. and *Vinson, T.S.*, 1993: Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. *Water, Air and Soil Pollute. 70*, 207-221.

Konev, E.V., 1977: *Physical Principals of Vegetation Matter Burning* (in Russian). Nauka, Novosibirsk. pp. 240.

Moiseev, N.N., *Alexandrov, V.V.* and *Tarko, A.M.*, 1985: *Man and Biosphere. An Experience in System Analysis and Model Experiments* (in Russian). Nauka, Moscow. pp. 282.

Molchanov, A.A., 1977: *Major Types of North Taiga Biogeocenoses* (in Russian). Nauka, Moscow. pp. 282.

Reference Book for Forest Taxation (in Russian) (eds.: *Zakharov V.K.*, *Trull O.A.*, *Miroshnikov V.S.* and *Ermakov V.E.*), 1962. Belorussia State Publ., Minsk, pp. 368.

Strakhov, V.V., *Filipchuk, A.N.* and *Shvidenko, A.Z.*, 1995: On changes in forest registration in Russia (in Russian). *Forestry 1*, 11-14.

Vloedbeld, M. and *Leemans, R.*, 1993: Quantifying feedback processes in the response of the terrestrial carbon cycle to global change: the modeling approach of IMAGE 2.0. *Water, Air and Soil Pollute. 70*, 615-628.

Vompersky, S.E. and *Utkin, A.I.*, 1988: *The Analysis of Forest Productivity Structure* (in Russian). Nauka, Moscow, pp. 240.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Burning Biomass in the Territories of the Former Soviet Eurasia: Impact on the Carbon Budget

Anatoly Shvidenko[1], **Sten Nilsson**[1], **Robert K. Dixon**[2], and **Vjacheslav Rojkov**[3]

[1] *International Institute for Applied System Analysis, A-2361, Laxenburg, Austria*

[2] *U.S. Support for Country Studies to Address Climate Change, 1000 Independence Ave. SW, Washington, DC 20585, USA*

[3] *V.V. Dokuchaev Soil Institute, Pyshevsky per. 7, 109017, Moscow, Russia*

Abstract—Wild forest fires, managed (prescribed) burning (in agriculture, forestry, and so forth), burning on agricultural lands, and use of biomass for energy production by industry and population are the basic sources of greenhouse gases caused by biomass burning in the vast territories of the former Soviet Eurasia. The total carbon (C) emissions in the atmosphere were estimated for 8 regions of the former Soviet Union (FSU), based on available statistics, numerous publications, and expert estimates.

The C emissions in the atmosphere caused by biomass burning was estimated as 299 Tg C/year in the 1990s. Annual areas of forest fires were estimated at 1.5 million ha on forested areas and 2.0 million ha on other categories of forest fund areas and state land reserves. Direct annual forest fire flux was estimated to have been about 58 million tons of carbon, and post-fire biogenic flux at about 92 million t C annually. 35 Tg C/year are emitted when wood is used as fuel for industrial and domestic purposes. From 103 Tg C produced annually by the agricultural sector, the biggest sources are managed burning on pastures and hayfields (26 Tg C/year) and burning agricultural wastes (77 Tg C/year). The remaining 11 Tg C includes peat fuel consumption and management burning.

The estimates are preliminary because of numerous uncertainties associated with incomplete data on managed burning as well as current statistics on biomass fuel consumption.

Key-words: wildfire, C emission, boreal forests, C budget, Russia.

1. Introduction

Burning of biomass is a significant source of emissions to the atmosphere in vast areas of the former Soviet Eurasia (all the independent countries of the former Soviet Union (FSU)). Unfortunately, some types of biomass burning are extremely difficult to quantify because of measurement problems, poor and incomplete statistics, and insufficient knowledge of some basic processes. *Fig. 1* presents a conceptual scheme of the basic C cycle components caused by biomass burning. The role of the components is significantly different for different regions of the territory of the FSU. The goal of this work was to develop the 'big picture,' then aggregate all calculations by the large, relatively homogeneous regions given in *Table 1*. In this table, Baltia includes Estonia, Latvia, and Lithuania; Southwest includes Ukraine, Belorus, and Moldova; Caucasus includes Armenia, Azerbaidjan, and Georgia; and Central Asia includes Kirgizstan, Tadjikistan, Turkmenistan, and Uzbekistan. The Russian Federation has been divided into European Russia, Ural, West Siberia, East Siberia, and Far East.

The results considered below are given as annual averages for 1988 through 1990. Information for the last several years is not as available, complete, and reliable as that of the last years of the Soviet Union.

Regional and global estimates of fire and post-fire emissions from boreal forests in the atmosphere vary greatly, as well as do the approaches used, models, and considerations of post-fire processes (*Auclair,* 1991; *Crutzen* and *Goldammer,* 1993; *Dixon* and *Krankina,* 1993; *Levine,* 1991; etc.). The final products of burning contain different materials, depending on many conditions (*Valendik* and *Gavel,* 1975; *Cofer et al.,* 1990, 1991; *Hegg et al.,* 1990). The composition of emissions from vegetation burning given by *Lobert* and *Warnatz* (1993) is: 80–85 percent CO_2 (from 50 percent in low-intensity smoldering fires to 99 percent in large fires), 7 percent CO (2–15 percent), 2–3 percent hydrocarbons (0.5 percent CH_4, about 1 percent NMHC, and 0.5 percent in the form of pure and aromatic hydrocarbons). These data are within range of *Andrea's* review (1991), according to which roughly 2 percent of emitted carbon are in the form of particulate organic carbon, and about 0.5 percent is elementary carbon. In our calculations we assumed that emissions from burning are composed of CO_2 and CO (95%), NH_4 and NMHC (3%) (taking into account a share of litter and peat fires), and particulate carbon from aerosols (2%). This assumption allows us to calculate the post-burning gas composition using the procedure developed by *Cahhon et al.* (1994).

Several authors have calculated the average C contents in forest combustibles (FC). Their estimates are 0.51 for ovendry wood, 0.48 for green parts (from 0.49 to 0.53 for needles), and 0.40 for the upper soil humus layer (*Vonsky,* 1957; *Filippov,* 1968; *Telizin,* 1973); for litterfall (pine, cedar) the estimates are 0.52–0.61, for litter 0.44–0.54 (*Vedrova,* 1995). Taking into account the large geographical variability of specific gravity of wood and the heterogeneity of forest combustibles, we used 0.50 as an average for the dry weight of phytomass and detritus (*Matthews,* 1993).

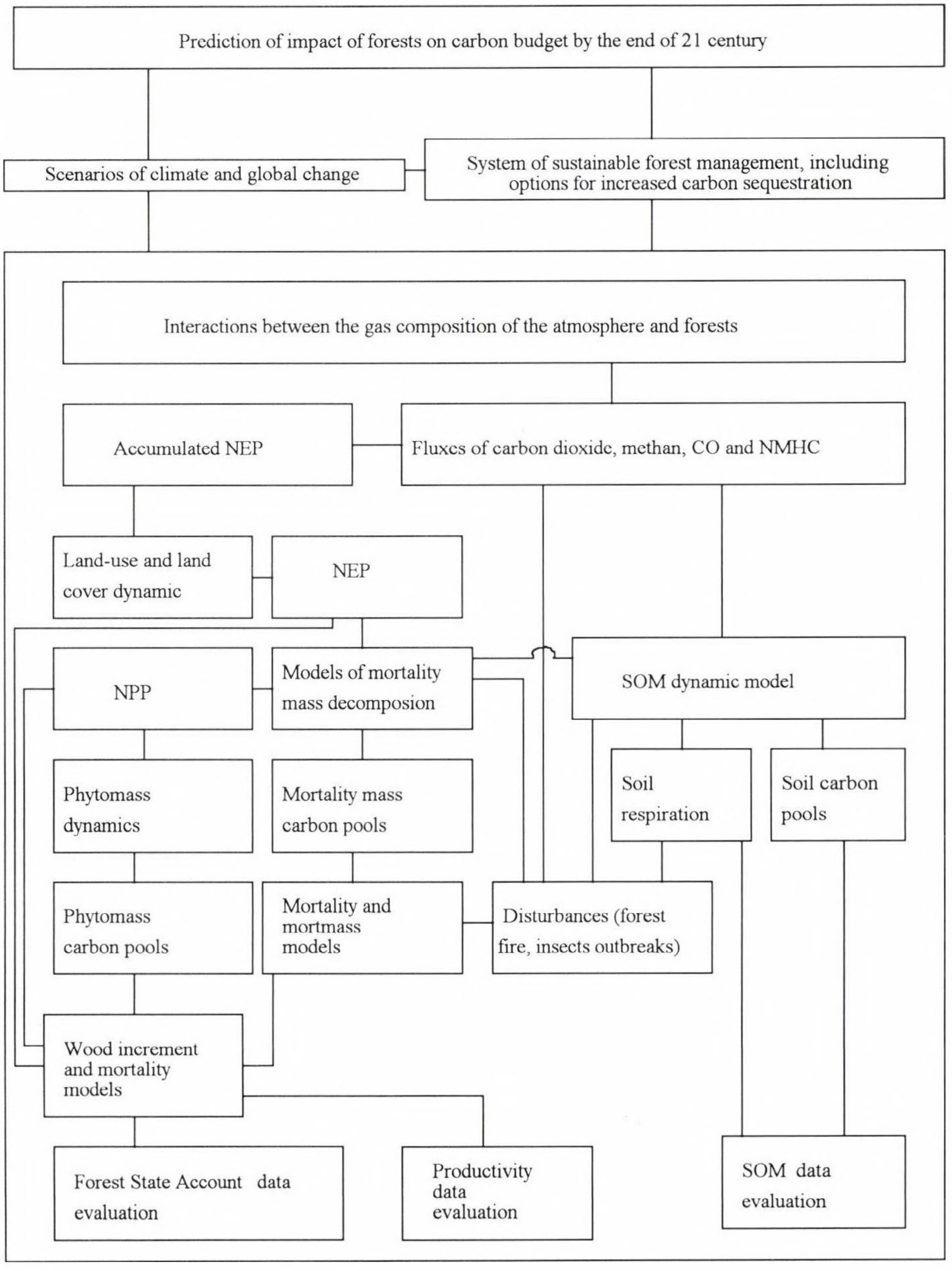


Fig. 1. Conceptual scheme of the analytical system. NEP = net ecosystem production, NPP = net primary production; SOM = soil organic matter.

Table 1. Areas (million ha) and population (th. persons) in the FSU. Sources: *Goscomstat USSR*, 1990; *IIA*, 1994

Region	Area	Including Forest Fund areas	Forested areas	Population	Including rural
Russia (including)	1707.5	1182.9	771.1	148673	39753
European part	348.5	209.4	130.2	95908	25613
Ural	2.4	42.1	35.8	20460	5223
West Siberia	242.7	150.6	90.1	15163	4353
East Siberia	412.3	315.4	234.5	9242	2657
Far East	621.6	507.2	280.5	7900	1907
Baltia	17.5	5.6	6.3	7813	2581
Southwest	84.5	18.4	16.0	66706	22391
Caucasus	18.6	4.7	4.1	16413	6980
Kazakhstan	271.3	21.4	9.6	16913	7256
Central Asia	127.7	19.4	7.2	31009	19098
FSU Total	**2227.1**	**1254.2**	**814.3**	**287527**	**99966**

2. *Forest Fires*

The Forest Fund Area of the FSU (about 69 percent of total lands of the FSU) includes forested areas (closed forests), unforested areas (areas on which forests are not growing temporarily, that is, burned forests and dead stands, sparse forests, clearcuts, and grassy glades), and non-forest lands such as mires, unproductive lands, and so forth. The total C emissions in the atmosphere (*TCF*) caused by biomass burning during year t^* can be expressed as (all results are given in Tg = Mt = 10^{12} g C/year)

$$TCF(t^*) = DF(t^*) + IPFF(tD), \tag{1}$$

where *DF* is the direct flux of carbon into the atmosphere during the fire in year t^*; *IPFF* is the following long-term indirect (postfire) biogenic flux during a period of decomposition of unburned organics tD.

Both *DF* and *IPFF*, as well as a relevant structure of *C* pools, depend on the nature of the processes, type of forest fire, strength and scale of fire, and the conditions under which a fire occurs.

Taking into account basic types and characteristics of forest fires in the boreal and temperate zones of the FSU, we used the following structure of carbon pools or their relevant aggregations:

- Three aboveground phytomass pools: commercial wood (stemwood and large branches with upper diameter greater than 8 cm under the bark, excluding the stump); branches (the rest of the crown wood, 1 cm < d < 8 cm); green parts (foliage and needles with woody twigs with d < 1 cm, understory, and green forest floor),
- Soil carbon pools: litter, coarse detritus material (roots, on- and in-ground coarse debris > 8 cm), fine detritus material (d < 8 cm), soil humus (labile and stabile parts).

DF and *IPFF* from (1) have been presented in the forms (2) and (3)

$$DF = C_{i,l,k,q} \; S_{i,l,k,q} \; FC_{i,l,k,q} \; , \tag{2}$$

where $C_{i,l,k,q}$ are coefficients of the burned forest combustibles, $S_{i,l,k,q}$ – estimates of forest fire areas, $(FC)_{i,l,k,q}$ – storage of forest combustibles (t/ha, dry matter).

Indices $i,l,k,$ and q depend on:

- Aggregated vegetation zone i ($i = 7$, aggregated from *Kurnaev* (1973): subarctic desert+tundra, forest tundra+sparse taiga+meadow forests, northern taiga, middle taiga, southern taiga, mixed forests + deciduos orests + forest steppe, steppe + semidesert + desert),
- Aggregated categories of land use l ($l = 4$: forested areas by groups of dominant species, unforested areas, non-forest lands, and peat areas),
- Type of forest fire k ($k = 4$: crown, on-ground, below ground, and peat fires),
- Type of forest combustible q ($q = 5$: two phytomass above-ground pools mentioned above, foliage, needls + twigs of d < 1cm; on-ground combustibles (green forest floor + woody debris + litter), and peat).

Postfire biogenic flux IPFF was estimated as

$$IPFF = F\{t,[(DUW + DPFD),\ SOL]\}_{\mathrm{i,l,k,q}}, \tag{3}$$

where F is some function depending on time t and on fluxes caused *DUW,* the decomposition of incombustible organics (mainly wood); *DPFD,* the decomposition of postfire die-back; and *SOL* soil organic losses. All variables from (3) depend on indices i,l,k,q.

It can be shown that the C flux in year t^* (G) caused by $DUW + DPFD$, which have been generated from organics delivered for decomposition during the previous period $tD_{i,j}$, can be estimated by the model as (*Shvidenko et al.*, 1994)

$$G_{i,j} = [\exp(\alpha_{i,j}) - 1] \sum_{\tau=0}^{\Phi+1} O_{i,j}(t-\tau) \exp(-\alpha_{i,j}\tau), \quad (4)$$

where $O_{i,j}(t)$ is the annual amount of organic matter added to the three decomposition pools j ($j = 3$: commercial woody pool, branches, 'green' pool) by zones I, α is a coefficient from a simple model of the decomposition rate of a homogeneous pool.

$$G(t) = \exp(-\alpha t), \quad (5)$$

where $\tau = t^* - t$, $0 < \tau < \Phi + 1$, and $\Phi = int\,[\,T(0.95) + 1]$. $T(0.95)$ is the time of decomposition of 95 percent of organic matter of a given pool.

The approach (4) underestimates the final result by about 5 percent by the cutting of the curves $G_{i,j}$ with $T(0.95)$ limits.

Annually burned areas $S_{i,l,k,q}$ have been inventoried only for protected forests, which consisted in the FSU of about 69 percent of the total area of the forest fund, including 92 million ha protected by on-ground control and 777 million ha protected by aerial methods. Fires were detected and extinguished on 585 million ha of this territory, while on the remaining area they were only detected. In 1989, the total area of protected forests in Russia was equal to 762 million ha (*Isaev,* 1991). Unprotected areas are basically situated in the forest tundra and sparse taiga of West Siberia (43 million ha in 1989), East Siberia (119 million ha), and Far East (249 million ha). The official statistical data on annual fires on protected forest fund areas from 1985 through 1990 are given in *Table 2*.

Statistical data on forest fires in 1986–1990 show that 98.8–99.6 percent of burned forest lands of the FSU were in Russia. During 1989–1992 the number of detected forest fires in Russia was 13,000–22,000; the total area of forest fires on protected areas was about 1.4 million ha (average) annually, including 1.1 million ha of forest land and 1.0 million ha of forested area (*Review...*, 1990, 1993).

Historical data on annual forest fires are incomplete and underestimate the real extent of forest fires in the past. Short time series are unreliable for historical reconstruction because of the highly variable spatial distribution of forest fires and their strong dependence on seasonal weather peculiarities. We tried to reconstruct a regional history of forest fires based on the following:

1. Regional data on burned areas, dead stands, grassy glades, and anthropogenic sparse forests (*Goscomles SSSR*, 1990).

Table 2. Number and area of forest fires in the FSU (first line) and Russia (second line) in 1985 – 1990. (*Goscomles SSSR*, 1991); CF – crown fire, OGF – on-ground fire, UGF – under ground fire

Year		Number of fires	Areas th.ha							Burned wood th.cub.m.	
			Total	Forest area	Forested area (including)				Non-forest land	Total	Timber
					Total	CF	OGF	UGF			
1985	FSU	14836	697	492	489	92	397	0	205	12055	7
	Russia	12031	694	489	395			0	205	12031	7
1986	FSU	22713	1173	715	705	210	494	1	458	26971	44
	Russia	16353	1160	706	694				454	26916	44
1987	FSU	16561	1327	572	538	124	415	1	755	10036	13
	Russia	13439	1323	569	536				754	10019	13
1988	FSU	24379	1017	792	762	145	618	1	225	37030	84
	Russia	19583	1013	788	758				225	36991	84
1989	FSU	28137	2070	1646	1514	252	1262	8	424	65420	88
	Russia	22517	2061	1639	1503				422	65242	88
1990	FSU	25345	1695	1384	1333	278	1054	1	311	23563	88
	Russia	18308	1687	1377	1327				310	23460	88

2. Regional dynamics of the forest fund categories mentioned above. The dynamics of such areas in 1966–1988 for forests under state forest management was: 44.9 million ha in 1966, 38.6 million ha in 1973, 25.3 million ha in 1988 and 26.6 million ha in 1983 (*Goscomles SSSR,* 1968, 1976, 1982, 1986, 1990, 1991).
3. Distribution of forests by age classes and types of age stand structure for main forest forming species.
4. Basic regularities of forest fires: frequency ('rotation period'), intensity, impact on successions, duration and character of postfire regeneration (*Melekhov,* 1948; *Utkin,* 1965; *Kurbatsky,* 1962; *Furjaev* and *Kireev,* 1979; *Chertovsky et al.,* 1987; *Valendik,* 1990; and many others).
5. Different historical records and publications (*Ministry...,* 1968; *Telizin,* 1988; *Valendik,* 1990; *Shetinsky,* 1994; and so forth).

In addition we assumed that:

1. The total input from organic matter decomposition in year t is proportional to the area of burned areas and dead stands.

2. Average ratios between different kinds of fires as well as the geographical distribution of fires are the same for all periods considered.
3. During 1800–1960 the areas of burned forests did not change significantly; the 1960s such areas uniformly decreased because of forest fire suppression. Burned areas and dead stands in 1961–1988 have been used as a baseline to extrapolate the curve $O_{ij}(t)$ in 1800–1960. Some relative corrections for the period 1947–1962 have been done based on official data on the percentage of burned areas in the forests under protection (percentage of forest fund areas): 1947–0.24, 1950-0.12, 1955-0.19, 1960- 0.13, 1962-0.10 *(Timoffev,* 1967).

Storage of forest combustibles was estimated based on regional and typological aggregations of numerous sources (*Academy...,* 1983; *Atkin* and *Atkina,* 1985; *Atkin* and *Smirnova,* 1983; *Bazilevich,* 1993; *Chertovsky et al.,* 1987; *Dichenkov,* 1993; *Grishin,* 1992; *Isaev,* 1966; *Ivanova,* 1985; *Kostirina,* 1975; *Kurbatsky,* 1970a, 1970b; *Kurbatsky* and *Ivanova,* 1987; *Matveev,* 1992; *Morozova* and *Lazareva,*1983; *Popova,* 1983; *Sementin,* 1978; *Sheshukov,* 1970, 1978; *Snitkin,* 1969, 1971; *Sofronov,* 1985; *Solovjov,* 1973; *Telizin,* 1970, 1988; *Vakurov,* 1975; *Valendik et al.,* 1977; *Zvetkov* and *Ivanova,* 1985; and many others).

The share of unburned above-ground biomass during forest fires varies significantly. Estimates of sizes of branches burned by crown fires vary from 0.7 mm to 4 cm (*Grishin,* 1992; *Ginsburg,* 1988). We used 1.0 cm as an average. The share of unburned phytomass can be 12–39 percent for mosses, 13 percent for lichens, and 10–20 percent for coniferous litterfall (*Valendik* and *Isakov,* 1978). During on-ground fires (small and middle intensity) the percentage of litter burned is up to 30 percent as reported from Ural (*Firsova,* 1960), up to 50 percent in Krasnojarsk kraj (*Popova,* 1978), and 20–50 percent in the Far East (*Saposhnikov,* 1993).

Our total estimate of annually burned areas of the forest fund lands and the northern areas of the state land reserves during the last 5–7 years are 3.5 million ha, including 3 million ha of forest fund areas, and 0.5 million ha of state land reserve areas.

Postfire dieback (*DPFD*) of trees varies greatly also, being heavily dependent on the type and intensity of fires and the dominant species. For on-ground superficial fire it equals to 6–12 percent, for on-ground steady fires: 15–20 percent, for litter fire: 30–50 percent, for turf fire: 60 percent, for peat fire: 70 percent, and for crown fire: 75 percent (averaged data). Variation is large, for example, for litter fire, 5–90 percent; for turf, 35–85 percent, and so forth. *Sibirina* (1989) identified dieback at about 60 percent (190 m^3/ha) in cedar stands (*Pinus korajensis*) of the Far East during the first 4 years after a steady on-ground fire, and the process was still going on. An increase in tree mortality increases from pine to larch, to cedar, to spruce stands (*Solovjov,* 1973; *Mishkov* and *Starodumov,* 1976; *Solovjov* and *Sheshukov*, 1976; *Sheshukov et al.*, 1978; *Mikhel,* 1984; *Sibirina,* 1989). The period of dieback caused by fire was estimated to be 3–5 years (*Balbishev,* 1958; *Solovjov* and *Krokhalev,* 1973; *Sofronov* and *Volokitina,* 1990). A part of postfire mortality is caused by outbreaks of secondary pests, especially xylophages (*Isaev,* 1966).

Many publications report the full destruction of stands after steady on-ground fire (*Zvetkov,* 1988; *Safronov* and *Volokitina,* 1990). Estimates of the Russian National Centre of Forest Pathological Monitoring (*Review...,* 1990, 1992) of forested areas damaged by different types of fire in 1990 are that 0.23 million ha forests would die (as forest ecosystem) within a 5-year period. The same estimates for 1991 and 1992 are 0.20 and 0.18 million ha, respectively. In the case of unfavourable weather conditions, this value can be substantially higher. Unfortunately, partial postfire mortality is not described in detail, and we used aggregated data from the above-mentioned and other publications. Generally, average post-fire mortality for different zones and types of forests was estimated as changing within relatively narrow limits, from 25 to 40 percent, and we used as a general average one third of initial growing stock. Additionally, we have evaluated the postfire mortality of lichens and mosses as 50 percent of their unburned amount (*Auclair,* 1985). The same assumption was made for understory vegetation (undergrowth and bushes).

Estimates of burned peat areas (including underground fires) are very uncertain. The two last estimates of peat areas in Russia (where 95 percent of all the mires in the FSU are located), as well as their carbon pool, differ two-fold. *Vompersky* (1994) estimated peat areas at 369 million ha, including areas with the depth of peat layer more than 0.3 m – 139 million ha. His estimates of the carbon pool in the peat areas is 97–133 Pg. *Botch et al.* (1995) estimated the total peatland area as 165 Mha and the peat carbon pool at 215 Pg. Statistics on peat fire do not exist. Underground and peat fires are often accounted as on-ground ones (*Sofronov* and *Volokitina,* 1990). Taking into account that peat areas comprise about of 25 percent of the forest fund, and the climatic conditions under which peat fires can arise occur two or three times a decade in basic forest zones (*Kurbatsky,* 1962; *Furjaev,* 1970; *Arzibashev,* 1974; *Gundar,* 1978; *Chervonny,* 1979; *Starodumov,* 1966; *Rjabukha,* 1973; *Gundar* and *Kostirina,* 1976), as well as specifics of annual large forest fire distribution, we used the following rather conservative expert estimates. The burned peat areas were estimated at 0.35 million ha (10 percent of the total annual average of estimated burned areas). We assumed that the upper 20 cm layer of peat areas is burned, and 40 percent of soil carbon is emitted in the atmosphere. The density of undrained peat was estimated based on *Vompersky et al.* (1975) to be from 0.05 to 0.10 t/m3, while the weight of dry peat (peat soil) in a 20 cm layer could be estimated as about 160 tons per ha. Total area of below-ground fires was estimated to be 12 thousand hectares (the average for 1989–1992 on protected areas was about 4 thousand hectares) with a depth of burning of 0.8 m (*Gundar,* 1978).

Postfire soil organic changes have a very complicated nature as the result of many processes that have mutually exclusive final results: postfire enhanced soil respiration, postfire replacement of carbon by water and wind, litter accumulation following postfire regrowth (forest or other vegetation), the character of forest-forming processes (regeneration by coniferous or other species), a changing water regime in wet areas, and so forth. We considered only postfire soil organic losses (*SOL* in (3)) and did not include in our calculations any impacts of postfire regeneration processes including post fire fertilization (for example, N-fixers), or heat melioration, and so forth, which are usual for the taiga and especially for all permafrost areas. *SOL* strongly depends on the type of fire, total storage, and share of burned *FC*. As a rule, prescribed burning and superficial on-ground fires do not cause any essential losses of soil organics in boreal forests (*Wells,* 1971). In many cases, there is a slight total increase of soil organics several years after a fire (see, for example, *McKee*, 1982; review by *Johnson,* 1992). On the contrary, steady on-ground, litter, and turf fires can cause considerable postfire decreases of humus content (40 percent during a 25 year period in the 60 cm top layer has been reported by *Sands* (1983) for *Pinus radiata* in Australia) but such results are an exception rather than a rule (*Dyrness et al.,* 1989, and others). Many Russian researchers give similar results, although very high losses of soil organics are not identified. As a general conclusion for taiga forests in the Far East, Siberia, and the European North, there are no essential changes in the organics of mineral horizons after most on-ground fires; a postfire rehabilitation of litter and soil organics occurs within 2–4 or 5–7 years (*Saposhnikov* and *Kostenkova,* 1984; *Orphanitskaja* and *Orphanisky,* 1959; *Firsova,* 1960; *Popova,* 1978; *Saposhnikov et al.,* 1993). More significant losses of soil organics have been reported for northern larch forests on permafrost (*Matveev,* 1992). Based on this information we estimated total postfire losses of soil humus as 7 percent of its average content in the top 1m layer.

The rate of decomposition of organic matter (*DUW+DPFD*) by different phytomass pools depends upon climatic zones, species composition, humidity, and so forth, and varies from about 200–250 years for commercial larch woods in forest-tundra on permafrost (*Ivshin*, 1993) to about 30 years for aspen and white birches in the southern Far East (our estimates). Even in a separate climatic zone the variation may be very large. For example, *Bogatiriev* and *Fless* (*Academy...,* 1983) reported for the Northern Taiga in the Komi Republic a period of litter decomposition of 100–300 years for wetlands and 2–10 years for relatively productive stands. Taking into account the uncertainties of the initial data and a very poor knowledge of the rate of decomposition in different biomass pools, we used very common average zonal data based on many publications (*Academy...*, 1983; *Vedrova et al. I,* 1989; *Bazilevich*, 1994; *Smoljaninov,* 1969; among others). For the litter pool α is changed from 0.038 (tundra) to 4.0 (steppe and semidesert), and $T(0.95)$, respectively, from about

80 years to 0.75. For a 'medium' wood pool α is 0.03–0.37, and $T(0.95)$ is 100 to 8.1. For commercial timber ('slow pool') α is 0.017 (forest tundra) to 0.13, and $T(0.95)$ is 180 to 23.

Humus generated from the on-ground phytomass decomposition was estimated at 2 to 11 percent of the annual input of organics (*Kononova,* 1984; *Orlovsky,* 1968), depending on climatic conditions and the structure of the die-back.

Total direct C emission during the year of the fire (*DF* in (1)) was estimated as 58.1 Tg C/year in 1990 (*Table 3*).

Table 3. Forest fire carbon emissions in 1990 caused by fires of 1990 expressed in Tg C/year

Type of land and type of fire	Area M ha	Emission Tg C/yr
Forested areas (including)		
Crown fires	0.25	5.6
On-ground fires	1.11	13.7
Unforested areas	0.45	4.5
Non-forested lands	1.35	8.4
Peat fires	0.35	22.4
Below ground fires	0.012	3.5
Total	**3.5**	**58.1**

Postfire biogenic flux (*PFFF)* was estimated by applying (4) to the above-mentioned carbon pools and vegetation zones. The C emissions in the atmosphere caused by the 'fast' ('green') pool was 36.5 Tg C/year; by the medium one, 7.5 Tg C/year; and by the 'slow' one (commercial timber), 43.2 Tg C/year; the total was 87.2 Tg C annually. A significant part of the fast pool is the soil organic losses (for example, for 1990, 17.9 Tg C/year from 36.5 Tg). Total annual release of carbon caused by forest fires in the FSU in 1990 was estimated as $TCF = 58.1 + 1.05 \times 87.2 = 150$ Tg C. About 99 percent of the result were caused by fires in the Russian forests.

Managed burning (prescribing burning in forests, fire cleaning of cut areas, and so forth) was different in the FSU forests two decades ago. Recent and current instructions do not recommend such activities, and statistics for it do not exist. Nevertheless, these operations are still carried out on a small scale. Based on available information from selected regions and personal communications, we estimated the total area to range from 0.15 to 0.20 million ha annually, comprising about 10 percent of the annually logged areas during 1980–1990. The fuel consumed was estimated at 20 t/ha of dry matter. It contributes about 2 Tg C annually.

3. Fuel Wood Consumption

According to official statistics, consumption of fuelwood harvested by the forest industry in 1990 was equal to 60.1×10^6 m^3 (*Burdin,* 1991, *Table 4*). Some of this wood is used for different technological purposes. We assumed that the share of burned wood is 80 percent; this gives 48.1×10^6 m^3 wood used as a fuel. In addition, about $13–18 \times 10^6$ m^3 of wood classified as 'waste' (unused by-products of saw mills, parts of stems left in logged areas, and so forth.) were used for fuel. Totally, 'industrial' fuelwood consumption was estimated as 66×10^6 m^3. The corresponding emissions are equal to 16.5 Tg C.

Table 4. Consumption of fuel wood in 1970–1989 (million m^3) (*Burdin,* 1991; personal communications: *Efremov,* 1995; *Sedykh,* 1995; *Chibisov,* 1995)

Region	Consumption of fuel wood by				Residential consumption
	1970	1980	1985	1989	1990
Russia	**64.1**	**61.6**	**64.4**	**56.1**	**54.7**
European Russia	32.6	27.1	28.2	23.4	14.8
Ural	11.4	9.5	10.2	8.4	13.1
West Siberia	5.2	5.5	5.3	5.3	13.1
East Siberia	9.0	11.5	12.8	11.8	7.9
Far East	5.9	8.0	7.9	7.2	5.8
Baltia	2.5	1.4	1.6	1.8	1.5
Caucasus	0.3	0.2	0.2	0.1	2.8
Central Asia	0.3	0.3	0.2	0.2	2.9
Kazakhstan	1.1	0.6	0.7	0.7	1.4
European Southwest	3.6	1.5	1.4	0.9	11.2
FSU	**71.8**	**65.6**	**68.4**	**60.1**	**74.5**
Wood wastes for fuel	17.4	13.9	17.9	18.4	–
Total	**89.2**	**79.5**	**86.3**	**78.5**	–

* - for 1975

Fuelwood for residential consumption includes locally harvested biomass such as biomass from thinning and sanitary cuts; dry wood; shrubbery, etc. No data on residential consumption are currently available. We used expert regional estimates of the average consumption of fuelwood per rural family. The efficiency of burning wood was estimated to be 90 percent. Fuelwood consumption by urban families has been estimated as 10 percent of consumption by rural families. Data on residential consumption given in Table 4 include an additional component of industrial wastes delivered to the population (8.74×10^6 m^3 in 1985, 12.34×10^6 m^3 in 1989, *Burdin,* 1991). Total residential consumption was estimated as 73.8×10^6 m^3, which corresponds to the annual C flux of 18.4 Tg.

The accuracy of the estimates of both industrial and domestic consumption cannot be evaluated in any formal way. Probably, some of the burned (unused) industrial waste is significantly underestimated. For example, according to an official conclusion of the former USSR State Committee on Forests (*Isaev,* 1991), output of lumber is about 44 percent of round wood. In 1989, 101.1×10^6 m^3 of lumber was produced (*Burdin,* 1991). It means that the actual wastes of wood processing were more than 120×10^6 m^3 (*Burdin,* 1991).

4. Consumption of Peat for Fuel

The peat reserves designated for industrial use are equal to 44.4×10^9 tons of peat; the possible production with the current infrastructure was estimated as 530×10^6 tons (*Sisoev,* 1968). Consumption of peat for fuel decreased significantly during recent decades (*Table 5*). Statistics of the last 5 years is not complete and reliable. Nevertheless, there is some evidence of an increase in peat fuel consumption during recent years, for example, annual peat fuel production in 1990–1992 in Russia was respectively 5.2, 4.7, and 7.8×10^6 t. The share of peat in total fuel production in Russia is very small, 0.2 percent in 1992, compared to 37.0 percent of oil, 47.9 percent of gas, and 14.0 percent of coal (*IIA*, 1994).

Table 5. Annual production of fuel peat in the FSU (standard moisture content; Gg/year)

Region	1965	1970	1975	1980	1985	1986	1987
FSU	**45747**	**57380**	**53836**	**21590**	**15987**	**19480**	**11445**
Russia	29406	39447	36424	13156	8382	10889	4212
Ukraine	4343	4084	4143	1597	2107	2286	2240
Belorus	8366	9241	9271	4486	4532	4799	4151
Latvia	1248	1490	1005	425	136	192	128
Lithuania	1699	2139	1888	1008	400	536	214
Estonia	670	972	1047	918	430	778	500

The probable estimate of current industrial production of peat fuel is about 12–14 million t. Domestic consumption is unknown. We assume that it is about 30 percent of the industrial production. This yields $16–18 \times 10^6$ t of peat.

Using conservative assumptions of burning efficiency, taking into account the shares of different peat types, decomposition rates, ash contents (*Table 6*), and average C content, the emissions of C were estimated to be 6 × 10^6 t C annually. That is much lower than the C emissions caused by using peat for fertilization; annual use in 1986–1990 was 92.3 × 10^6 t for Russia alone (*Romanenko et al.,* 1995).

Table 6. Regional characteristics of peat. HM – high-moor peat; TM – transition-moor peat; LM – low-moor peat (terminology is used according to Gosstandart SSSR (1985))

Region	Storage distribution, %			Peat decomposition degree, %			Ash content, %		
	HM	TM	LM	HM	TM	LM	HM	TM	LM
Leningrad	76	14	10	26	23	25	3.0	5.0	6.4
Pskov	37	28	35	20	28	26	2.6	4.8	6.1
Novgorod	75	9	16	20	28	27	2.4	4.4	6.7
Arkhangelsk	77	14	9	21	30	33	2.3	7.4	8.8
Komi	47	17	37	31	37	33	3.7	5.5	10.2
Vologda	47	30	23	17	30	33	3.2	4.5	6.8
Kirov	30	20	51	34	37	49	3.8	5.9	13.5
Tyumen	58	15	27	22	29	30	5.6	6.8	8.9
Tomsk	59	19	21	18	29	43	5.0	7.2	15.6
Omsk	4	7	89	18	36	37	3.9	6.9	10.4
Novosibirsk	23	13	64	15	26	30	4.8	8.5	8.9
Khabarovsk	2	38	60	21	31	29	10.8	15.9	20.3
Sakhalin	98	1	1	15	31	46	3.9	19.3	32.6

5. Biomass Burning in the Agricultural Sector

The estimates of biomass burning in the agricultural sector are quite uncertain because of the lack of required data. The major sources of C emissions in the atmosphere from the agricultural sector are the burning of agricultural waste and managed burning of pastures and hayfields. The aggregated characteristics of the agricultural sector of the FSU are given in *Table 7* (*Goscomstat SSSR,* 1988). Some decrease in agricultural land areas was observed after 1988. The last land-use survey in Russia (1993) included 210.6 × 10^6 ha of agricultural lands, including 130.0 × 10^6 ha of arable lands, 19.4 × 10^6 ha of hayfields, and 58.9 × 10^6 ha of pastures (*Romanenko et al.,* 1995).

Table 7. Distribution of agricultural lands (million ha) by regions of the FSU.

Region	Agricultural lands Total	Arable lands	Hayfields	Pastures	Area under crops
Russia	218.3	133.9	23.6	59.3	119.7
Baltia	7.5	5.1	0.7	1.6	4.9
Southwest	53.8	42.1	3.4	6.8	41.0
Caucasus	8.7	2.8	0.5	4.6	2.6
Kazakhstan	195.7	35.7	4.9	154.8	35.6
Central Asia	72.7	7.9	0.3	63.6	7.7
Total FSU	**556.7**	**227.5**	**33.4**	**290.7**	**211.5**

The usual approach to estimating the amount of agricultural residue is to use the average ratio of 1:1 between crop and the residue (*Seiler* and *Crutzen,* 1980; *Andrea,* 1991). *Palz* and *Chartier* (1980) used the ratio 1:1 for grain to straw. In order to calculate the biomass burned in the agricultural sector we used regional data on crops (*Goscomstat SSSR,* 1989) and the ratio between crops and agricultural waste by main agricultural cultures. For cereals the share of stubble used was 30 percent, and the total mass of straw has been calculated as twice that of the crop. 40 percent of straw was included in the burning biomass, as well as 50 percent of the agricultural waste of technical cultures. Based on these assumptions and the crop data for basic agricultural plants (grain, 210×10^6 t; leguminous plants, 10×10^6 t; and so forth) we estimated that the emissions of C into the atmosphere caused by burning of agricultural wastes is about 78×10^6 t/year. This value includes agricultural residue used for heating.

Stubble burning occurs in Krasnodar and Stavropol oblasts, some regions of Ukraine, and in some other areas. Total areas have been estimated as 11 million ha (data obtained from the Dokuchaev Soil Institute, Moscow), yielding an annual C source in the range of 1.5 to 2 million t C.

Prescribed burning on pastures, and, partially, hayfields are conducted in many regions. Our area estimates are based on regional expert estimates and, to same extent, on data from the remote sensing inventory made in 1986–1988 (only selected forest steppe and steppe territories were surveyed). The total estimate of areas of prescribed burning is 25 million ha annually or about 8 percent of the total area of pastures and hayfields. Estimates of consumed fuel vary greatly, depending basically on climatic conditions and anthropogenic loads, from 0.3–0.5 t dry matter in southern semidesert up to 4–6 t/ha for meadows (*Bazilevich,* 1993; *Gorodezky et al.,* 1978, and others). The total result, calculated at the regional scale, was 26 Tg C annually.

Other impacts considered (for example, burning extracted peat, burning crop areas were not significant (*Table 8*). We estimated that these impacts contribute 3 million t of C annually.

Table 8. Cereals and technical crops destroyed by fire in Russia (annual average for 1988-1993). Source: *Ministry of Internal Affairs*, 1995

Year	Number of fires for cereals	Cereals destroyed by fire, $\times 10^3$ t	Number of fires for technical crops	Technical crops destroyed by fire, $\times 10^3$ t
1988	230	9.8	5641	111.4
1989	258	8.0	9504	225.9
1990	304	6.6	8377	135.1
1991	334	13.8	10328	164.2
1992	523	60.4	10974	165.2
1993	482	8.5	11864	166.6
Average		17.8		161.4

6. Conclusion

The total C emissions caused by biomass burning and reported in this study are equal to 299 Tg C annually. About 50 percent of this amount is contributed by natural forest fires. It is less than has been reported in previous publications (*Dixon* and *Krankina,* 1993; *Stocks,* 1991). Emissions from fuelwood consumption are significantly higher and emissions from agricultural waste are of the same magnitude that have been reported by *Seiler* and *Crutzen* (1980), *FAO* (1986), and *Andrea* (1991).

The uncertainty of these results cannot be estimated in a formal way. The use of fuzzy theory methods (use of *a priori* probabilities for formal calculations of final uncertainties) leads to the conclusion that the final uncertainty of the aggregated result ranges from 30 to 35 percent with a (*a priori*) probability of about 0.7.

References

Academy of Sciences of the USSR, 1983: *Role of Litter in Forest Biogeocenosis*. Short reports of the All-Union meeting. Nauka Publ., Moscow. (Ananko, 5-6, Atkin, 9–10, Atkin, Smirnova, 10–11, Bogatirev, Fless, 22–23, Bondareva, 24–25, Popa, 159–160, Rikhter, 173–174, Zarik, 206–207) (in Russian).

Andrea, M.O., 1991: Biomass burning: its history, use, and distribution and its impact on environmental quality and global change. In *Global Biomass Burning Atmospheric, Climatic, and Biosperic Implications* (ed.: *J.S.Levine*) 3–21. MIT Press, Cambridge MA USA.

Arzibashev, E.S., 1974: *Forest Fires and Fighting with Them* (in Russian). Forest Industry, Moscow.

Atkin, A.S. and *Smirnova, L.I.*, 1983: Generation and accumulation of litter in forests of the Southern Ural. In *Litter and its Role in Forest Biocenosis 10-15.* Institute of Forest and Wood the (IFW), Siberian Division of the Academy of Sciencies of the USSR, Krasnojarsk, (in Russian).

Atkin, A.S. and *Atkina, L.I.*, 1985: Storage of on-ground combustible materials in pine standsm. In *Prediction of Forest Fires,* 92–101. IFW, Krasnojarsk, (in Russian).

Auclair, A.N.D., 1985: Postfire regeneration of plant and soil organic pools in *Picea mariana-Cladonia stellaria* ecosystems. *Can. J. For. Res. 15*, 279-291.

Auclair, A.N.D., 1991: Forest fires as a recent source and a sink of CO_2 at mid-high northern latitudes. Paper presented at the US EPA Environmental Research Laboratory, Corvallis, OR, USA.

Balbishev, I.N., 1958: Fire stability of different forest types in southern taiga and forest steppe of West Siberia (in Russian). *Forest Management (Lesnoje Khozjaistvo)*, No. 10, 43–48.

Bazilevich, N.I., 1993: *Biological Productivity of Ecosystems of Northern Eurasia.* Nauka, Moscow (in Russian).

Botch, M.S., *Kobak, K.I.*, *Vinson, T.S.*, and *Kolchugina, T.P.*, 1995: Carbon pools and accumulation on peatlands of the former Soviet Union. *Glob. Biogeoch. Cycles 9,* No. 1, 37–46.

Burdin, N.A. (ed.), 1991: *Forest Complex of the USSR.* Parts 1 and 2. VNNIPEILesprom, Moscow, (in Russian).

Cahhon, D.R., Jr., *Stocks, B.I.*, *Levine, S.*, *Cofer III, W.R.*, and *Pierson J.M.*, 1994: Satellite analysis of the severe 1987 forest fires in northern China and southern Siberia, *Journ. of Geoph. Res. 99*, D9, 18627–18638.

Chertovsky, V.G., *Semenov, B.A.*, and *Zvetkov, V.F.*, 1987: *Sub-Tundra Forests.* Agropromizdat, Moscow, (in Russian).

Chervonny, M.G., 1979: *Aircraft Forest Protection.* Forest Industry, Moscow, (in Russian).

Cofer, W.R., *Levine, J.S.*, *Winstead, W.L.*, and *Stocks, B.J.*, 1990: Gaseous emissions from Canadian boreal forest fires. *Atmos. Environ. 24A,* 1653–1659.

Cofer, W.R., *Levine, J.S.*, *Winstead, W.L.*, and *Stocks, B.J.*, 1991. New estimates of nitrous oxide emissions from biomass burning. *Nature, 349,* 689–691.

Crutzen, P.J., and *Goldammer, J.G.* (eds.), 1993: *Fire in the Environment. The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires.* Report of the Dahlem Workshop held in Berlin 15–20 March 1992. John Wiley and Sons.

Dichenkov, N.A., 1993: *Ways to Increase the Effectiveness of Forest Fire Danger Evaluation.* Institute of Forest, Byeloruss Academy of Sciences, Gomel, Byeloruss, (in Russian).

Dixon, R.K., and *Krankina, O.N.*, 1993: Forest fires in Russia: carbon dioxide emissions into the atmosphere. *Can. J. For. Res. 23,* 700–705.

Dyrness, C.T., *van Cleve, K.*, and *Leviston, J.D.*, 1989: The effect of wildfire on soil chemistry in four forest types in interior Alaska. *Can. J. For. Res. 19,* 1389-1396.

FAO, 1989: *Yearbooks of Forest Products 1987* (1976–1987). FAO, Rome.

Filippov, A.V., 1968: Some pyrological properties of forest combustibles. In *Problems of Burning and Extinguishing,* VNIIPO, Moscow, 351–358, (in Russian).

Firsova, V.P., 1960: About influence of forest fires on soils. In *Papers of the Institute of Biology of the Ural Filial.* Acad. of Sci. of the USSR, *16*, 41–52, (in Russian).

Furjaev, V.V., 1970: Ground water table influence on fire in wetland and swamp forests in areas between Ket and Chulim Rivers. In *Problems of Forest Pyrology,* IFW, Krasnojarsk, 186–218, (in Russian).

Furjaev, V.V. and *Kireev, D.M.*, 1979: *Study of Post Forest Fire Dynamics on Landscape Basis.* Nauka, Novosibirsk, (in Russian).

Ginsburg, A.S., 1988: *The Planet Earth in Postnuclear Epoch.* Nauka, Moscow, (in Russian).

Gorodezky, A.V., *Bistrizkaja, T.L.*, *Osichnjuk, V.V.*, *et al.*, 1978: Energetic and ecochemical characteristics of steppe ecosystems autotrofic components. In *Natural Fodder Resources of the USSR and Their Use* (ed.: *T.S. Khachaturov*), 116–132. Nauka. Moscow, (in Russian).

Goscomles SSSR (before 1988: Gosleshoz). Forest Fund of the USSR. 1968, 1976, 1982, 1986, 1991. The USSR State Committee of Forest, Moscow, (in Russian).

Goscomstat SSSR, 1985: *Peat. Terms and Definitions. State Standard 21123-85.* The USSR State Committee on Standards, Moscow, (in Russian).

Goscomstat SSSR, 1988: *Agriculture in the USSR.* The USSR State Committee on Statistics, Moscow, (in Russian).

Grishin, A.M., 1992: *Mathematical Modelling of Forest Fires and new Methods of Struggle with Them.* Nauka, Novosibirsk, (in Russian).

Gundar, S.V. and *Kostirina, T.V.,* 1976: On prediction of peat fires. In: *Increase of Productivity of Forests in the Far East.* Reports of DalNIILKh, *18,* 98–101, Khabarovsk, (in Russian).

*Gundar, S.V.,*1978: On soil fires characteristics. In *Burning and Fires in Forests,* 142–144. IFW, Krasnojarsk, (in Russian).

Gundar, S.V. 1978: Soil fires in the Nishne Amur River basin, their preventive inspection and extinguishing. IFW, SD, AS of the USSR, Krasnojarsk, pp. 24, (in Russian).

Hegg, D.A., Radke, L.F., Hobbs, R.A., et al., 1990: Emissions of some trace gases from biomass fires. *J. Geophys. Res. 95,* 5669-5675.

IIA, 1994: *New Russia'94.* Joint venture 'All Moscow', International Information Academy, Moscow (in Russian).

Isaev, A.S., 1966: *Stem Insects on Dahurica Larch.* Nauka, Moscow (in Russian).

Isaev, A.S. (ed.), 1991: *Forestry at the Boundary of the XXI century.* Ecology, Moscow (in Russian).

Ivanova, G.A., 1985: Seasonal dynamics of onground burning material accumulation in pine stands with grasses and red bilberries floor cover. In *Prediction of Forest Fire,* 101–110. IFW, Krasnojarsk (in Russian).

Ivshin, A.P., 1993: *Influence of Air Pollutions of Noril'sk Metallurgical Enterprise on the State of Spruce-Larch Stands* (in Russian). Inst. of Ecology of Plants and Animals, RAS, Ekaterinburg.

Johnson, D.W., 1992: Effects of forest management on soil carbon storage. *Water, Air, and Soil Pollutions 64,* 83–120.

Kobak, K.I., 1988: *Biotical Compounds of the Carbon Cycle.* Gidrometeoizdat Press, Leningrad (in Russian).

*Kononova, M.M.,*1984: Organic matter and soil fertility. *Soil Science (Pochvovedenie), 8,* 6–20 (in Russian).

Kostirina, G.V., 1975: On fire danger of Khekhzir enterprises forest enterprises. In: *Utilization and Regeneration of Forest Resourses of the Far East,* 331–335. Far Eastern Forestry Institute, Khabarovsk (in Russian).

Kurbatsky, N.P., 1962: *Technics and Tactics of Extinguishjng Forest Fires.* Forest Industry, Moscow (in Russian).

Kurbatsky, N.P., 1970a: Investigations of quantity and properties of forest combustible materials. In *Problems of Forest Pyrology.* IFW, Krasnojarsk (in Russian), 3–58.

Kurbatsky, N.P., 1970b: Classification of forest fires. In *Problems of Forestry.* IFW, Krasnojarsk (in Russian) 384–407.

Kurbatsky, N.P. and *Ivanova, G.A.,*1987: *Forest Fire Danger in Forest Steppe Pine Stands and Possibilities to Decrease it.* IFW, Krasnojarsk (in Russian).

Kurnaev, S.F., 1973: *Forest Vegetation Regionalization of the USSR.* Nauka, Moscow (in Russian).

Lobert, J.M. and *Warnatz, J.,* 1993: Emission from the combastion process vegetation. In *The Ecological, Atmospheric, and Climatic Importance of Vegetation Fire* (eds.: *P.J. Crutzen* and *J.D. Goldammer*). John Wiley & Sons, New York, 15-37.

Levine, J.S. (ed.), 1991: *Global Biomass Burning/Atmospheric, Climatic, and Biospheric Implications.* MIT Press, Cambridge MA USA.

Matthews, G., 1993: *The Carbon Contents of Trees.* Forestry Commission, Technical Paper 4, Edinburgh UK.

Matveev, P.M., 1992: *Post Fire Consequences in Larch Biogeocensis on Permafrost.* Marijsky Polytechnical Institute, Joshkar-Ola (in Russian).

McKee, W.H., 1982: *Changes in Soil Fertility Following Prescribing Burning on Coastal Plain Pine Sites. Res. Paper SE-234.* Southeastern Forest Experiment Station, USDA Forest Service.

Melekhov, I.S., 1948: *Influence of Fires on Forest.* Goslestekhizdat, Moscow (in Russian).

Mikhel, V.A., 1984: Influence of main factors for die-back of trees under on-ground fires. In *Use and Regeneration of Forest Resourses of the Far East*. Reports of DalNIILKh, *26*, 124-129 (in Russian).
Ministry of Internal Affairs of the Russian Federation, 1995: Statistical data on crops and technical cultures disturbed by fire by the subjects of the Russian Federation in 1988–1993. Official information, Moscow (in Russian).
Ministry of Forestry of the Russian Federation, 1968: *Forestry and Forest Management in Russia*. Forest Industry, Moscow (in Russian).
Mishkov, F.F. and *Starodumov, A.M.*, 1976: On the influence of fire on the cedar stand with ash and shrubs. In *Increase of Productivity of Forests in the Far East*, Reports of DalNIILKh, *18*, 106–107 (in Russian).
Morozova, R.M. and *Lazareva, I.P.*, 1983: Role of litter in the biological turnover of Karelian Pine biogeocenosis. In *Role of Litter in Forest Biogeocenoses* (in Russian). Nauka, Moscow, 131-133.
Orlovsky, N.V. (ed.), 1968: *Forest and Soil* (in Russian). Krasnojarsk Book Publishing, Krasnojarsk.
Orphanitskaja, V.G. and *Orphanitsky, Ju.A.*, 1959: Influence of fire cleaning of cut areas on some soil properties. In *Reports of the Arkhangelsk Forest Technical Institute*, *19*, Arkhangelsk, 85–89 (in Russian).
Popova, E.D., 1978: Duration of pyrogenic influence for properties of forest soils. In *Burning and Fires in Forest*. IFW, Krasnojarsk, (in Russian) 185–186.
Popova, E.N., 1983: Role of the forest litter in the nutrition of phytocenoses in Middle Priangar'e (in Russian). In *Role of Litter in Forest Biogeocenoses*. Nauka, Moscow, 160-161.
Review of the Sanitary State of Forests in 1990, 1990: All-Russia Informational and Research Centre of Forest Resourses. Moscow (in Russian).
Review of the Sanitary State of Forests in Russia in 1991, 1992: National Centre of Forest Pathological Monitoring. Federal Service of Forest Management of the Russian Federation, Moscow (in Russian).
Review of the Sanitary State of Forests in Russia in 1992, 1993: National Centre of Forest Pathological Monitoring. Federal Service of Forest Management of the Russian Federation, Moscow (in Russian).
Rjabukha, A.A., 1973: Contra-fire measures on drainage areas. *Forest Management (Lesnoje Khozjaistvo)*, No. 10, 55–66 (in Russian).
Romanenko, G.A., Tjutjunnikov, A.I., Shutkov, A.A., and Makarov, I.P., 1995: *Agroindustrial Complex of Russia*. Russian Academy of Agricultural Science, Novosibirsk (in Russian).
Sands, R., 1983: Physical changes to sandy soils planted by radiata pine. In *IUFRO Symposium on Forest Site and Continuous Productivity*. USDA FS, GTR PNW-163, Portland, Oregon, 146-152.
Saposhnikov, A.P. and *Kostenkova, A.F.*, 1984: Influence of forest fire on litter in cedar forests of the Southern Sikhote-Alin and peculiarities their regeneration. In *Dynamic Processes in Forests of the Far East*. Far Eastern Scientific Centre, Academy of Science of the USSR, Vladivostok, 139–146 (in Russian).
Saposhnikov, A.P., 1994: Personal communication (DalNIILKh).
Sedykh, V.N., 1995: Personal communication (IFW).
Seiler, W. and *Crutzen, P.J.*, 1980: Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climate Change 2*, 207–247.
Sementin, V.L., 1978: Factors influencing the fire risk in Pine and Larch plantations (in Russian). In *Prediction of Forest Fires*. Inst. of Forest and Wood, Sib. Div., Ac. of Sci. of the USSR, Krasnojarsk, 78-83.
Shaposnikov, A.P., Selivanova, G.A., Il'ina, T.M., Djukarev, V.N., Bugovez, G.A., Gladkova, G.A., Gavrenkov, G.I. and *Shil'zov, A.S.*, 1993: *Soil Generation and Peculiarities of Turnover in Mountain Forests of Southern Sikhote-Alin'* (in Russian). DalNILKh, Khabarovsk.
Sheshukov, M.A., 1970: Some pyrological properties of forest combustible materials, *Scientific Reports*, DalNIILKh, No. 10, 253–263 (in Russian).
Sheshukov, M.A., 1978: Influence of forest fire on development of taiga biocenoses. In: *Burning and Fires in Forests*. IFW, Krasnojarsk, 166–167, (in Russian).

Sheshukov, M.A., Solovjov, V.I. and *Naikrug, I.B.*, 1978: Fire influence of different factors on damage of stands and tree species. In *Use and Regeneration of Forest Resources in the Far East*, Reports of DalNIILKh, *20*, 145–150 (in Russian).

Sheshukov, M.A., Savtchenko, A.P. and *Peshkov, V.V.*, 1992: *Forest Fires and Fighting Them in the Far Northeast*. DalNIILKh, Khabarovsk (in Russian).

Shetinsky, E.A., 1994: *Forest Protection and Forest Pyrology*. Ecology, Moscow (in Russian).

Shvidenko, A., Nilsson, S. and *Roskov, V.*, 1994: Possibilities for increasing carbon sequestration by implementation of rational forest management in Russia. Manuscript submitted for publication in *Water, Air and Soil Pollution*.

Sibirina, L.A., 1989: Postfire break-up of the cedar-broadleaf forests. In *Results of Researches in the Far Eastern Forests and Problems of Improvement of Multi-purpose Use of Forests*, 118–119. DalNIILKh, Khabarovsk (in Russian).

Sisoev, D.V. (ed.), 1968: *Atlas of Peat Resources of the USSR*. Moscow.

Smoljaninov, I.I., 1969: *Biological Turnover of Matter and Increase of Forest Productivity*. Forest Industry, Moscow (in Russian).

Snitkin, G.V., 1969: Reserves of combustible materials in some types of larch stands and thickets of dwarf pine in the basin of the Kolima River. In *Results of Investigations*, DalNIILKh, *9*, 443–446 (in Russian).

Snitkin, G.V., 1971: Reserves of onground cover in some types of forests in the Magadan region. In: *Biological Resources of the Far East Terrestrial North*, *2*, 129–133 (in Russian).

Sofronov, M.A., 1985: Pyrological characteristics of vegetation in the upper basin of the Turukhan River. In *Forest Fire and Fighting with Them*, 106–117. IFW, (in Russian).

Sofronov, M.A. and *Volokitina, A.V.*, 1990: *Recommendations on Forest Fire Protection in the Bogged Forests of Southern Taiga Forests in Siberia*. IFW, Krasnojarsk (in Russian).

Solovjov, V.I., 1973: Consequences of fires in pine and larch forests of the Amur district. In: *Utilization and Regeneration of Forest Resources in the Far East*. Reports of DalNIILKh, *15*, 173–181.

Solovjov, V.I. and *Krokhalev, A.K.*, 1973: About some post-fire changes in pine stands. In: *Utilization and Regeneration of Forest Resources in the Far East*, Reports of DalNIILKh, *15*, 182–189. Khabarovsk (in Russian).

Solovjov, V.I. and *Sheshukov, M.A.*, 1976: Dynamics of postfire die-back in spruce stands with green mosses. In *Increase of Productivity of Forests in the Far East*. Reports of DalNIILKh, *18*, 85–90 (in Russian).

Starodumov, A.M., 1966: *Nature of Forest Fires in the Far East*. Forest Industry, Moscow (in Russian).

Stocks, B.J., 1991: The extent and impact of forest fires in northern circumpolar countries. In *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications* (ed.: *J. Levine*). MIT Press, Cambridge MA USA, 197–202.

Telizin, G.P., 1973: Elementary composition of forest combustibles in the Far East. In *Utilization and Regeneration of Forest Resources in the Far East*, Reports of DalNIILKh, *15*, 351-358 (in Russian).

Telizin, G.P., 1970: Characteristics of forest combustible materials and their connection with peculiarities of burning. In *Scientific Reports of DalNIILKh, 10*, 248–252. Khabarovsk, (in Russian).

Telizin, G.P., 1988: *Forest Fires, Their Prevention and Extinguishing in Khabarovsk Region*. DalNIILH, Khabarovsk (in Russian).

Timofeev, N.V., 1967: *Forests – a National Wealth for the Soviet People* (in Russian). Forest Industry, Moscow.

Utkin, A.I., 1965: *Forests of Central Jakutia* (in Russian). Nauka, Moscow .

Vakurov, A.D., 1975: *Forest Fires in the North*. Nauka, Moscow (in Russian).

Valendik, E.N. and *Gevel, N.F.*, 1975: Share of burned forest materials. In *Problems of Forest Pyrology*, 127–137. IFW, Krasnojarsk (in Russian).

Valendik, E.N., Vorobiov, O.B., and *Matveev, A.M.*, 1977: Prediction of forest fire contours. In:

Characteristics of the Processes of Burning in Forest, 52–66. IFW', Khrasnojarsk (in Russian).
Valendik, E.N. and *Isakov, R.V.,* 1978: Intensity of forest fire. In: *Prediction of Forest Fires*, 40–55. IFW, Krasnojarsk (in Russian).
Valendik, E.N., 1990: *Struggle with Large Forest Fires.* Nauka, Novosibirsk (in Russian).
Vedrova, E.F., 1995: Personal communication (IFW).
Vedrova, E.F., Shugalej, L.S. and *Beskorovajnaja, I.N.,* 1989: Development and properties of litter in planted forest biogeocenoses. In *Results of Studies of Far Eastern Forests, and Problems of Intensification of Multiple Forest Use* (ed.: *D.F. Efremov*) (in Russian). DalNILKh, Khabarovsk, 77-78.
Volokitina, A.V. and *Sofronov, M.A.,* 1979: Moisture, content of water, and intensity of onground cover burning in forest. In *Modelling in Forest Fire Protection,* 45–85. IFW, Krasnojarsk (in Russian).
Vompersky, S.E., Sabo, E.D., and *Formin, A.S.,* 1975: *Forest Drainage Melioration.* Forest Industry, Moscow (in Russian).
Vompersky, S.E., 1994: Role of mires in Carbon rotation. In *Biogeocenic Peculiarities of Mires and Their Rational Use*, 5–37. Reports from XI Sukachev memory meetings. Nauka, Moscow (in Russian).
Vonsky, S.M., 1957: *Intensity of On-ground Forest Fire and its Practical Meanings.* Leningrad Forestry Institute, Leningrad (in Russian).
Wells, C.J., 1971: Effect of prescribed burning on soil chemical properties and nutrient availability. In: *Proceedings of Prescribed Burning Symposium,* 86–99. Southeastern Forest Experiment Station, USDA Forest Service, Asheville NC USA.
Zvetkov, P.A. and *Ivanova, V.V.,* 1985: Slash on clear-cut areas after harvesting by aggregate harvesting machinery. In *Forest Fires and their Consequences*, 124–132. IFW, Krasnojarsk (in Russian).
Zvetkov, V.F., 1988: Problems of forest regeneration in the Kola peninsula. In *Problems of Forest Regeneration in the Taiga Zone of the USSR,* 242–243. Siberian Division, Academy of Sciences of the USSR, Krasnojarsk (in Russian).

PART II

Greenhouse Gas Emissions in Countries of Central and Eastern Europe, and Newly Independent States

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Greenhouse Gas Emission Inventory in Latvia

I. Apene[1], **N. Lucans**[2], and **E. Lammers**[3]

[1] *Department of Environmental Protection of the Latvian Ministry of Environment Protection and Regional Development*

[2] *Latvian Environment Data Centre, the Latvian Ministry of Environment Protection and Regional Development*

[3] *Institute for Environmental Studies, The Netherlands*

Abstract—Latvia's National Communication under the United Nations Framework Convention on Climate Change (FCCC) is about to be officially released. Included in Latvia's National Communication are an inventory of greenhouse gas emissions, a description of mitigation policies and measures, and a projection of greenhouse gas emissions untill the year 2000. Major problems in the development of the emission inventory were the lack of statistical data and the incompatibility of Latvian statistical data with international statistics. In the base year, 1990, total CO_2 emissions were equal to 22.973 Gg, CH_4 emissions were 158.9 Gg, and N_2O emissions — 2.4 Gg. CO_2 sequestration is relatively high in Latvia and reached 50 percent of total CO_2 emissions. Projections of future greenhouse gas emissions show that these are expected to decrease by about 30 percent. Important elements of a climate change policy are related to transformations in the energy sector. The newly established Baltic Forum provides a good opportunity for cooperation in the region. All Baltic states encounter similar problems in preparing their National Communications and emission inventories.

Key-words: national communication, emission inventory, statistics, climate change policy.

1. Introduction

Latvia ratified the United Nations Framework Convention on Climate Change (FCCC) on February 23, 1995. In anticipation of the reporting obligations under the UN FCCC, Latvia started to prepare its National Communication in late 1993. Included in Latvia's National Communication are an inventory of greenhouse gas emissions, a description of mitigation policies and measures, and a projection of greenhouse gas emissions to the year 2000. The transition from a centrally planned economy to a market-based economy was the main difficulty in the preparation of the National Communication. Since Latvia became independent in August 1991 after the collapse of the USSR, legislative, economic, and governmental reforms have impacted the development of statistics. The transition process will continue until 2000. Because of the transition process, estimates of greenhouse gas emissions may be inaccurate, the impacts of policies and measures are hard to assess because implementation of planned policies and measures is uncertain, and the projections of emissions to 2000 are highly uncertain because of the unpredictability of future economic conditions.

This paper describes the organizational aspects of the development of Latvia's emissions inventory. It will present a short summary of the results of the emissions inventory and will provide more details concerning Latvia's statistics and emissions from forestry. In addition, some details are included concerning future emissions, possible mitigation options, and Baltic cooperation activities.

2. Organizational Aspects

The preparation of Latvia's first National Communication was coordinated by the Ministry of Environmental Protection and Regional Development. An inter-ministerial core team and steering team was established to perform the work so that all relevant ministries and institutions participated in the study, including the Ministry of Transport, the Ministry of Economy, the Ministry of Agriculture (Department of Agriculture and Forestry Department), the Ministry of Finances (Department of Forecasting), the State Committee of Statistics, and the Energy Agency of Latvia.

The Government of the Netherlands provided funding and technical assistance to the project. A joint Latvian-Polish-Dutch project, Country Case Study of Greenhouse Gas Sources and Sinks, and Potential Measures in Latvia, was initiated to form the basis for a close cooperation between Dutch experts (from the Institute of Environmental Studies), Polish experts (the Polish Foundation for Energy Efficiency) (FEWE) and the Latvian core team. The experience of Poland with emissions inventories proved to be a valuable contribution to the project.

The Latvian project commissioned the Latvian Development Agency with a scientific project called the Forecasts of Greenhouse Gas Emissions in Latvia. This agency used an input-output model for the projections of greenhouse gas emissions in 2000 which used the results of the emissions inventory as input for the model.

3. Statistical Problems in Latvia

Major problems of compiling the emissions inventory were the lack of statistical data and the incompatibility of Latvian statistical data with international statistics. Before independence in 1991, Latvian statistics were taken by the Latvian State Committee for Statistics and followed the Soviet statistical system.

This created major problems, especially, in the developpment of an energy balance which is needed to calculate CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) inventory methodology is based on the international system of energy statistics which differs in fomat and structure from that of the Soviet system. Moreover, the Soviet statistical data is not complete because not all fuel combustion activities were taken into account. To solve these problems and to arrive at a complete and fairly accurate energy balance estimate, all available data sources (both Latvian and Russian) have been examined and evaluated. Based on this evaluation and on recommendations provided by Latvian statistics and energy experts, Polish energy experts from FEWE proposed a 1990 energy balance. The proposal was formally adopted as the 1990 energy balance by the Latvian Government in 1994.

Also, the transportation data in Latvia was different from that used by the IPCC inventory methodology. Expert opinion was used for transforming the Latvian data into the IPCC format.

Since independence, reforms to the Latvian statistical system are being made. However, these reforms will probably not be completed before the year 2000. Current problems stem from radical changes in Latvia's economic and industrial performance. Because of privatization, data collection is quite problematic and incomplete. For example, the total consumption of gasoline is not known, because kerosene is imported by private companies and total quantities are not reported.

4. Latvia's Inventory of Greenhouse Gas Emissions

In accordance with the UN FCCC, 1990 is designated as the base year. The economic decline caused by transition processes took place shortly after 1990. Latvia's inventory included CO_2, CH_4, N_2O, NO_x, CO, and NMVOC and followed the approach outlined in the draft IPCC guidelines for national greenhouse gas inventories (*IPCC/OECD,* 1994). Major results are shown in *Table 1*.

Table 1. Greenhouse gas emissions in Latvia in 1990 (Gg)

GHG source and sink categories	CO_2	CH_4	N_2O	NO_x	CO	NMVOC
Total emissions and sinks	**22976.3**	**158.937**	**2.38**	**90.13**	**363.1**	**62.722**
1. Energy	22605.6	4.167	1.03	90.13	363.1	55.324
2. Industrial processes	370.7					
3. Solvent and other product use						7.398
4. Agriculture		111.27	1.351			
5. Land use change and forestry	(-14300)					
6. Waste		43.5				

Sources: *State Committee for Statistics,* 1992a, 1992b

Energy

The energy sector is the most important source of greenhouse gas emissions in Latvia. Emission factors applied to calculate greenhouse gas emissions were taken from the IPCC guidelines. However, these are often inadequate because fuel combustion technologies in Eastern Europe differ from those in western industrialized countries. Research is needed on country-specific emission factors.

Industry

Cement production is the only source of industrial CO_2 emissions. It is a relatively small source and accounts for only 1.5 percent of total CO_2 emissions.

Solvent Use

Data on air pollution from the Latvian Environment Data Centre have been used. Due to a lack of data, only stationary sources have been taken into account.

Agriculture

Agriculture is the most important source of CH_4 emissions. Emission sources are enteric fermentation processes of animals and anaerobic decay of manure. The simplest method from the IPCC methodology has been applied to calculate these emissions. The application of fertilisers is the main source of N_2O emissions in Latvia.

Forestry and Land Use Change

CO_2 emissions and removals from forestry have been estimated following the methodology of the United States Environmental Protection Agency (EPA) (*Dixon et al.,* 1991). This method was selected because the forest types distinguished these were more applicable to Latvia than the forest types distinguished in the IPCC methodology. The IPCC methodology makes a distinction between tropical, temperate, and boreal climate zones. Latvia, however, is situated in the hemiboreal zone. Forest types that can be found in Latvia are coniferous and deciduous forest types. The coefficients provided in the IPCC methodology could not be applied to Latvian national data. The methodology provided by the EPA allowed Latvia to use national data available for the various species of trees, including average age, cover, and annual increment. Forestry data were taken from the State Forest Service Data Base maintained by the Forestry Department of the Ministry of Agriculture. Emission coefficients applied to estimate carbon emissions and sequestration were taken from the EPA methodology. Further research is needed to arrive at country-specific emission coefficients.

Annual CO_2 sequestration by forests amounts to 20,600 Gg. Total CO_2 emissions from forestry are estimated at 6,280 Gg (*Table 2*). These estimates are based on harvest statistics. The harvested wood is used as fuelwood, exported, or used in furniture manufacturing and construction. Because of an increase in total standing life biomass, net CO_2 removals in Latvia are relatively high (about 50 percent of total anthropogenic CO_2 emissions). When Latvia was the part of the USSR, large reforestation and afforestation projects were carried out on its territory. Growth of these new forests, in combination with better management strategies, led to a relatively large increase of biomass per hectare.

Latvia does not agree with the approach taken in the IPCC guidelines to calculate emissions and removals from forestry. According to this methodology, emissions from forestry are accounted for in the country where timber is produced. Thus, emissions from exported wood that occur in other countries are the responsibility of Latvia. Latvia feels that emissions from forestry should be treated in the same way as emissions from fossil fuels. The latter are accounted for in the country of consumption. However, in the preparation of the current inventory, the approach taken in the IPCC guidelines has been followed.

Table 2. CO_2 emissions and removals by forests in 1990 (Gg)

CO_2 sequestration	20600
CO_2 emissions due to harvest	6280
– fuelwood burned	1428
– export	628
– other[1]	4224
Net CO_2 removals	14300

[1] E.g., furniture production, construction.

5. Future Emissions and Possible Mitigation Options

Using simplified economic input-output modelling techniques, greenhouse gas emissions in 2000 have been estimated. Assumptions have been made for economic development. Indicators for gross domestic product, energy production, manufacturing, and transport are all expected to decrease by 20-50 percent. Because of this economic decline, total CO_2 emissions are expected to decrease by about 26 percent compared to 1990 levels. CH_4 emissions are expected to drop by 28 percent, and N_2O emissions by 40 percent. Aggregate emissions expressed in CO_2 equivalents are expected to decrease by 27 percent.

Therefore, Latvia has no problems in meeting its objective of stabilizing greenhouse gas emissions in 2000 at 1990 levels. However, because economic growth is expected after 2000, post-2000 emissions will most likely rapidly increase. A medium- to long-term mitigation strategy is required to reduce this increase in greenhouse gas emissions. No specific climate change policy has yet been developed in Latvia. However, mitigation objectives often coincide with other environmental objectives. These have been formulated in the Environmental Protection Policy Plan (EPPP) which was approved by the Cabinet of Ministers on April 24, 1995.

One of the most powerful tools for implementing climate policy is legislation. The role of the Natural Resource Tax is important. A revised tax is underway and is expected to be introduced in 1995. The revised tax will include a CO_2 tax imposed through an excise tax on fossil fuels. However, to date the taxes have been ineffective because of rapid economic changes and high inflation.

The most important elements of climate change policy are related to reforms in the energy sector. Currently, energy saving strategies are being developed within the context of a PHARE 3 project. Also, the EPPP stresses the principles of efficient utilization of energy resources and encourages energy savings in the energy production and transformation sector.

6. Cooperation Activities Between Baltic States

The problems discussed in this paper concerning the preparation of a National Communication and the development of an emission inventory are similar in the other Baltic States. Similar statistical problems exist in all three Baltic States. Until now, cooperation between the Baltic States mainly took place at workshops for Annex II countries and informally by regular phone contacts. In 1995, the Baltic Forum was established under the leadership of the Baltic Council of Ministers. The Baltic Forum will be funded by the European Union and it will support workshops related to environmental problems. This will provide an excellent opportunity for constructive cooperation between the Baltic States in the future.

References

Dixon, R.K., Schroeder, P.E., and *Winjum, J.K.* (eds.), 1991: *Assessment of Promising Forest Management Practices and Technologies for Enhancing the Conservation and Sequestration of Atmospheric Carbon and Their Costs at the Site Level.* US Environmental Protection Agency Environmental Research Laboratory.

IPCC/OECD, 1994: Draft Guidelines for National Greenhouse Gas Inventories.

State Committee for Statistics of the Republic of Latvia, 1992a: Statistical Yearbook of Latvia—1991. A/S 'Preses nams', Riga.

State Committee for Statistics of the Republic of Latvia, 1992b: Latvia in Figures 1991—Collection of statistical Data. State Committee for Statistics of the Republic of Latvia, Riga.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Estimating CO_2 Emissions from Energy in Slovakia Using the IPCC Reference Method

Jiři Balajka

PROFING Comp. Ltd.,
82721 Bratislava, Slovakia

Abstract—Compiling the inventory of CO_2 emissions from energy is one of the basic steps in developing the national GHG mitigation policy. The CO_2 inventory was developed in Slovakia using the IPCC reference approach. While estimating emissions we encountered the following methodological problems: limited compatibility of input data from energy statistics with the IPCC Methodology; sectoral categories used in the energy statistics in Eastern European countries do not match the IPCC categories; the use of fuels to produce long-living products containing carbon in Slovakia is different from the one described in the IPCC methodology; input data can be misleading and double counting may occur.

Key-words: CO_2 emissions, IPCC methodology, carbon stored, energy statistics, emission factors, Slovakia.

1. Introduction

In Slovakia, energy-related CO_2 emissions exceed greenhouse gas (GHG) emissions from other sources. Describing these emissions is very import for the developing of a national GHG mitigation policy. The IPCC reference methodology (*IPCC,* 1993) provides a useful guidance to estimating energy related CO_2 emissions. At first, we considered this methodology to be too simplistic and suggested that the more sophisticated technology-oriented method should be used to compile the Slovakian national inventory. However, experience with preparing the First National Communication for Slovakia has changed our opinion. Simplicity is the main advantage of the IPCC Reference Approach. For example, to estimate emissions from metallurgy it is simpler to balance carbon on the basis of coking coal consumption than trace the fate of such products as coking gas and blast oven gas, which is necessary if the technology-oriented approach is applied. A similar situation exists in oil refineries where it is easier to describe the balance of carbon using the oil consumption values than account for all technological streams represented by different refinery gases. However, in spite of its transparency, the application of the IPCC Reference Approach ('top-down') is associated with the following difficulties:

- Limited compatibility of the national energy statistics with the IPCC Methodology,
- Sectoral categories used in the energy statistics in Eastern European countries do not match the IPCC categories,
- The use of fuels to produce long-living products containing carbon in Slovakia is different from the one described in the IPCC Methodology,
- Input data can be misleading and double counting may occur.

This paper describes results of inventorying energy-related CO_2 emissions in Slovakia and summarizes our experience with using the IPCC Reference Approach.

2. *Results of the First Inventory of Energy-related CO_2 Emissions in Slovakia*

Table 1 summarizes CO_2 emissions from energy in 1990 estimated using the IPCC default emission factors (*IPCC*, 1993). The fuel consumption data from the national energy statistics were used as inputs (*Federal...*, 1991; *Salomounová* and *Růžička*, 1995). The aggregated emission factors in individual sectors are influenced not only by the type of fuel used, but also by the share of carbon stored in products, such as plastic and fertilizer.

The share of individual sectors in the total CO_2 emissions in 1990 is illustrated in *Fig. 1*. *Fig. 2* shows the trend in energy-related CO_2 emissions for the period from 1980 to 1992. Decrease in CO_2 emissions is connected with the political and economic changes in Central and Eastern Europe after 1989–1990.

3. *Available Energy Statistics and the IPCC Methodology*

The available statistics for the former Czechoslovakia can be used as input data for estimating emissions from energy according to the IPCC reference approach (*Federal...*, 1991). These data, however, are based on the different fuel classification than the one outlined in the IPCC methodology (*IPCC*, 1993). The main differences between the two fuel classifications can be summarized as follows:

- The light and residual fuel oils, which are classified in the national statistics as two groups, are aggregated into one group by the IPCC.
- The national statistics treats lignite and brown coal as two distinct categories, while in the IPCC methodology they are treated as a single fuel type.

Table 1. Slovakian inventory of energy-related CO_2 emissions in 1990; PES - primary energy supply, EF - emission factor[1]

	PES (PJ)	CO_2 (Gg)	Total CO_2 (Gg)	EF ($kgCO_2/GJ$) fuel	EF ($kgCO_2/GJ$) sector
Fuel Combustion Activities					
1. Energy and transformation					
Coal	143.1	12772	15679	89.3	81.0
Oil	19.4	1164		59.8	
Gas	31.1	1743		56.0	
2. Industry					
Coal	110.9	10934	21155	98.6	64.2
Oil	98.6	4190		42.5	
Gas	120.2	6031		50.2	
3. Transport					
Coal	0.0	0	3628	-	71.1
Oil	51.0	3628		71.1	
Gas	0.0	0		-	
4. Commercial & Institutional					
Coal	35.3	3355	6153	95.2	74.4
Oil	6.7	512		76.6	
Gas	40.8	2286		56.0	
5. Residential					
Coal	49.5	4686	6383	94.7	80.2
Oil	1.5	95		62.4	
Gas	28.6	1603		56.0	
6. Agriculture & Forestry					
Coal	4.6	437	2035	94.5	74.6
Oil	19.5	1422		72.9	
Gas	3.1	175		56.0	
7. Total					
Coal	343.3	32185	55033	93.7	72.0
Oil	196.8	11010		56.0	
Gas	223.8	11839		52.9	

[1] Sectoral emission factors are the weighted average values from the mix of liquid, solid, and gaseous fuels in each sector and reflect the fact that part of the carbon from primary fuel input ends up stored in long-living products.

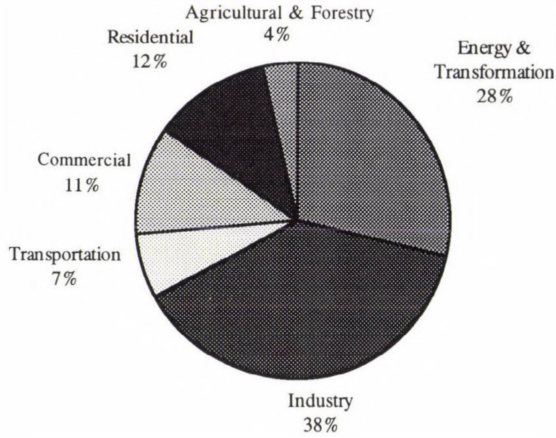


Fig. 1. Energy-related CO_2 emissions in Slovakia in 1990.

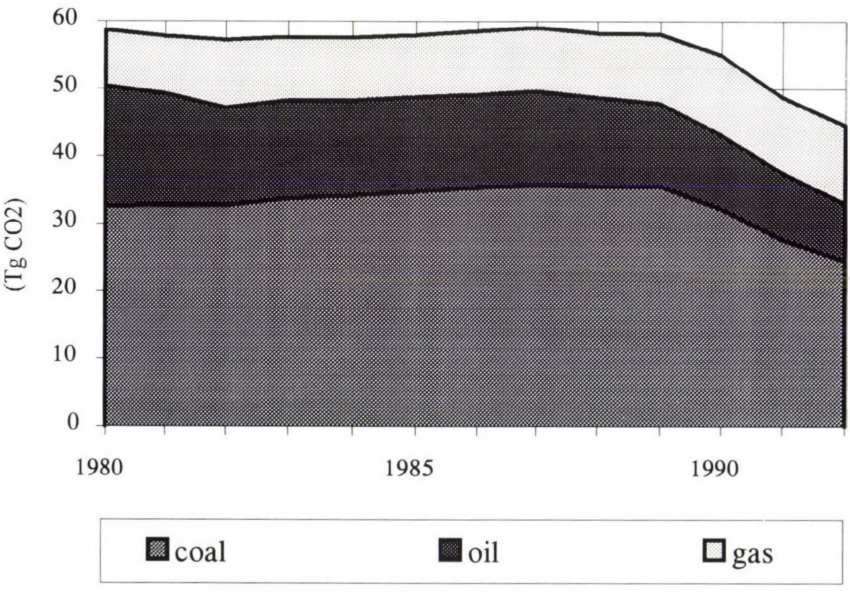


Fig. 2. Energy-related emissions of CO_2 in Slovakia from 1980 to 1992.

- LPG is reported in the national statistics as a gaseous fuel, while according to the IPCC classification LPG is a liquid fuel.
- The IPCC methodology (*IPCC*, 1993) traces carbon contained in gases produced from coking coal (coking gas, blast oven gas) on the basis of the coking coal consumption. The individual balances of these gases are not addressed by the IPCC reference approach. These balances, however, should be estimated when we consider emissions disaggregation by sectors ('bottom-up' approach). If these gases are treated as gaseous fuel in individual sectors the differences in final values produced by the 'top-down' (reference) and 'bottom-up' IPCC approaches increases. It seems appropriate to place these gases into groups based on primary fuels that serve as their sources. Oven gas and coking gas should be placed into the 'Solid Fuels' group and refinery gas should be placed into the 'Liquid Fuels' group. In the Slovakian inventory, consumption of these gases is described in the *Energy & Transformation* sector.

4. Disaggregation of Fuel Consumption and Emissions by Sectors

The national energy statistical data (*Federal...*, 1991) are provided by economic sector. However, restructuring of input data is necessary in order to follow the IPCC Methodology for reporting the energy-related CO_2 emissions (*IPCC*, 1993). The restructuring of input data from energy statistics was conducted according to the following rules (*Salomounová* and *Růžička*, 1995):

A. Distribution of fuel consumption between the *Energy & Transformation* and *Industry* sectors

- Fuel consumption at public power and cogeneration plants is allocated to the *Energy & Transformation* sector.
- Fuel consumption at industrial cogeneration and heating plants for electricity production is allocated to the *Energy & Transformation* sector.
- Fuel consumption at industrial cogeneration and heating plants for heat production is allocated to the *Industry* sector.

B. Fuel consumption in the *Transportation* Sector

In the area of transportation the national statistics allocates gasoline and diesel fuel consumed by cars and trucks that belong to industrial enterprises to the *Industry* sector, while gasoline and diesel fuel consumed by personal cars is allocated to the *Residential* sector. According to the IPCC method, transportation fuel consumption should be reported under the *Transportation* sector.

5. Estimation of Stored Carbon: the IPCC and National Approaches

The IPCC method of calculating stored carbon is based on the product's balance typical for western refineries and petrochemical industries. In Slovakia, the composition of petrochemical products that store carbon is slightly different.

Feedstocks from crude oil are used for the production of polyethylene and propylene, which in turn become ingredients of plastic materials and artificial fibres. Aggregated production data for plastic and man-made fibres are provided in the Statistical Yearbook of the Slovak Republic. The natural gas is used to produce urea, which also stores the carbon. The production data for plastics and man-made fibres together with urea production data were used to develop preliminary estimates of carbon stored in products. *Table 2* compares results of the national approach with values obtained using the IPCC Methodology (*IPCC*, 1993).

The fraction of carbon stored in bitumen and lubricants according to the national statistics is equal to 68.7% of the IPCC default value. This difference, however, comprises only 2.2% of the national CO_2 emissions.

Table 2. Comparison of the domestic and the IPCC methodology of estimating stored carbon in Slovakia

Product	Feed stock	Chemical composition	Carbon fraction	Production (Gg)	Carbon stored (Gg)	
					Domestic approach	IPCC approach
Urea	Natural gas	$(NH_2)_2CO$	0.200	29	5.6	192.3
Plastic material	Crude oil	CnH_{2n+2}	0.857	482	404.8	650.8
Man-made fibres	Crude oil	CnH_{2n+2}	0.857	124	104.6	
Bitumen	Crude oil				210.3	210.3
Lubricants	Crude oil				10.7	10.7
Coal Oils and Tars	Coking coal				0.1	0.1
Total					**736.1**	**1064.2**

6. Misleading Input Data and Double Counting

The following inaccuracies and uncertainties in the Slovakian CO_2 inventory should be considered and possibly corrected in the next national inventory:

- *Table 3* shows results of preliminary estimation of emission factors by the locally developed method in comparison with the IPCC default values. These results are based on composition of fuels reported by individual suppliers. The final values of domestic carbon emission factors will be prepared on the basis of average values for all fuels consumed in Slovakia in 1990. The calculation of total energy-related CO_2 emissions using these factors and comparison of these emissions with those estimated using the IPCC default methodology will be provided in the final Slovakian GHG inventory.

- Other inaccuracies in the inventory can be caused by the imprecise fuel consumption data and incorrect heating values. The data from energy statistics will be compared with the information on fuel consumption and fuel calorific values available from the National Emission Inventory (REZZO) in order to determine uncertainties in the national fuel consumption balance.
- The incorporation of gas losses from distribution network into the national carbon fuel balance can cause double counting. The volume of natural gas fugitive emissions must be determined from consultations with gas utilities.
- Additional uncertainty can be caused by differences in values of fuel consumption and fuel calorific values reported by fuel suppliers and fuel consumers.

Table 3. Preliminary comparison of the domestic and the IPCC default values of carbon emission factors [kg C/GJ]; HFO - heavy fuel oil, LFO - light fuel oil

	Anthracite	Steam coal	Lignite	Coke	HFO	LFO	Gasoline	Kerosene	Diesel fuel
IPCC	25.80	25.80	26.10	29.50	21.1	21.10	18.90	19.60	20.00
National factors	24 - 27	24 - 27	25 - 30	29.30	21.0	20.09	19.70	19.70	20.10

7. Conclusions

The IPCC method of estimating energy-related CO_2 emissions was used in Slovakia for preparing the first national inventory. Our experiences with the IPCC method can be summarized as follows:

- The IPCC methodology can ensure that the aggregated CO_2 emission inventory is valid and no fuels and sources are omitted.
- The national energy statistics can be easily adapted to the IPCC Methodology (*IPCC*, 1993). Some fuels have to be transferred into different categories in order to use default emission factors as required by the IPCC Workbook (*IPCC*, 1993).
- The national energy statistics follow the existing structure of economic sectors. The restructuring of the national energy statistics is necessary in order to follow the IPCC Methodology for reporting CO_2 emissions. The

main problem is re-allocating fuel consumed in the *Energy & Transformation* and *Industry* sectors. The other problem is the correct allocation of fuel inside the *Transportation* sector.

- The IPCC method of stored carbon accounting is based on the product balance of western refineries and petrochemical industries. The proposed domestic method is based on the direct balance of stored carbon derived from the data on production of such carbon-containing products as lubricants, bitumen, plastic and urea. The amount of stored carbon obtained from using domestic accounting method comprises 68.7% of the value derived using the IPCC default method. This difference represents 2.2% of the total national CO_2 emissions.
- The use of national statistical data for calculating energy-related CO_2 emissions may lead to certain inaccuracies, uncertainties and double counting. While preparing the next national GHG emission inventory we will focus on the development of national carbon emission factors and on comparing the input data from energy statistics with the data from the National Emissions Inventory (REZZO).

References

Federal Statistical Office, 1991: *Statistical Yearbook of SFR.*

IPCC, 1993: *IPCC Draft Guidelines for National Greenhouse Gas Inventories*, IPCC/OECD.

Salomounová and *Růžička*, 1995: Tvorba, riadenie a pouitie databázy v sektore energetiky, PHARE Energy Project A4, Janury 1995.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Methane Emissions at Russian Gas Industry Facilities

Anatoly Bordiugov

Russian Joint-Stock Company 'Gazprom',
Stroiteley Str., 8, 117939 Moscow, Russia

Abstract—Methane emissions from the gas industry pose serious environmental and economic problems in Russia. A significant barrier to reducing methane emissions from the natural gas industry is the lack of readily available natural gas industry data and an established methodology to estimate methane emissions. While the Global Environmental Fund (GEF) funded program has been established to reduce greenhouse gas emissions in Russia, additional funding is needed to support data collection and to assure accurate and consistent methane emission estimates. This report presents methane emissions estimates from the gas industry. It also outlines a methodology for estimating methane emissions and proposes measures to assure more accurate estimates of methane emissions in the future.

Key-words: methane, Russia, natural gas, greenhouse gases.

1. Introduction

All known efforts to quantify gross natural gas (methane) losses in Russia offer contradictory results, for example according to the UN data overall losses are equal to 14% of the total amount of produced gas, while according to *Rabchuk et al.* (1991) this number does not exceed 10%. The purpose of this report is to evaluate current Gazprom methane emissions and to suggest steps to minimize uncertainty associated with current efforts to estimate emissions from Russian gas industry facilities.

2. Description of the Russian Gas Industry

The Russian Gas Industry, resting on a stable resource base, has rapidly developed in recent years (*Table 1*).

With the transitions to more efficient methods of national hydrocarbon resource management, resources in the Russian Federation are being consumed more rationally. As a result, growth in gas production began to fall in 1991. By 1993, a total of 577.7 (in 1994, 570.7) billion actual cubic meters of gas were produced in Russia.

Table 1. Basic characteristics of the Russian Gas Industry

	1980	1985	1990	1991	1992	1993	1994
1. Gas production, 10^9 m^3/year	435	643	770	709	640.4	577.7	570.7
2. Delivery of gas to gas transmission pipelines	403	603	767	682	654	–	–
3. Total compressor station power, 10^9 kW	17.6	35.6	46.2	39.2	37	–	–
4. Proportion of gas turbines compared to total compression	0.817	0.840	0.849	0.820	0.8	–	–
5. Gas consumption for internal needs during main transport, 10^9 m^3	30.5	52.3	63.1	54.4	51.6	49.75	56.31
6. Proportion of gas used during transport, %	7.6	8.7	8.2	7.8	7.9	–	–
7. Losses, 10^9 m^3/year (% of production)	4.5 (1.03%)	9.93 (1.54%)	9.2 (1.2%)	9.1 (1.42%)	8.03 (1.25%)	7.37 (1.27%)	8.12 (1.42%)

The largest portion of gas is used for the production of electric power (including industrial power plants), representing about 54 percent of the total amount of gas used in Russia. The industrial sector accounts for approximately 33 percent of total gas consumption while the communal-residential sector makes up about 13 percent.

The widespread use of natural gas, the most environmentally benign fuel of all the fossil fuels, is anticipated to improve air quality and have other positive effects (*Gritsenko*, 1993).

The gas industry, however, may also negatively impact the surrounding environment due to harmful atmospheric emission (*Table* 2). As shown by the statistical data presented, methane represents 60 percent of emissions from the gas industry.

Table 2. Quantification of the technogenic emissions from Gazprom Enterprises (thousands metric tons)

	1991	1992	1993	1994
Stationary source emissions:	3212	2489	2428	2405
— particulates	6.6	5.1	4.9	4.7
— sulfur dioxide	59.2	42.3	38.7	42.6
— carbon oxides	533	528	513.7	500.0
— nitrous oxides	534	396	317.2	239.9
— natural gas	1774	1324	1380.1	1450.7
— volatile organic compounds	133	117	98.0	94.4
— other	172	76.6	75.4	72.7

3. Method of Determining Emissions

There is no direct measurement of natural gas emissions at Gazprom facilities. Emission levels (*E*) can be estimated using the following equation:

$$E = Q - q_{inp} - q_{sn} \pm q_{pkhg} \pm \Omega, \quad (1)$$

where Q is amount of gas produced in actual cubic meters, q_{inp} - delivery of gas to customers in cubic meters, q_{sn} - internal gas usage in cubic meters, q_{pkhg} - gas flux into (out of) underground storage, and Ω - change in the gas volume within the pipeline system over the calculation period in cubic meters.

Measurement uncertainties associated with measuring changes in gas volume at all points from production to end-use are the primary influence on the quantification of emissions (losses). However, gas losses due to accidents in

Russia are not considered when estimated harmful atmospheric emissions. On average 70 accidents occur at Gazprom facilities annually, increasing the amount of gas emitted into the atmosphere.

In short, it is clear that the method for determining atmospheric natural gas emissions from production, transmission and distribution must be strengthened. Also, the availability of reliable data on emission reduction efforts must be improved so that successful emission reductions can be incorporated into emissions estimates. Data collection and analysis for providing numeric estimates of reliability have yet to be performed (*Zittel*, 1993).

4. Classification of Sources of Natural Gas Loss and Quantification of Loss Volumes

Gross gas loss was determined by calculating technically grounded standard consumption and gas loss volumes for various gas industry operations. The total volume amounted to about five percent of production.

The distribution of the gross gas losses among the major emission sources at Gazprom is presented in *Table 3*.

5. Program of Work for Gas Industry Greenhouse Gas Emissions

In addition to causing environmental damage, methane emissions negatively affect the Gazprom competitiveness. If natural gas losses were reduced by a factor of two, the economy would benefit from profits worth hundreds of millions of American dollars.

According to current economic mechanisms established by environmental protection authorities in Russia, companies responsible for methane emissions will face an environmental tax or fine at the rate of 50 rubles per tone of methane. Financial penalties will also be imposed for multiple violations of methane emissions standards.

The Global Environmental Fund (GEF) has allotted resources for establishing a project to reduce greenhouse gas emissions from the Russian gas industry in Gazprom and Mintopenergo (Ministry for Fossil Fuels Energy). To address the problem effectively, a coordinating committee and working group have been established to develop and carry out the emissions reduction program.

6. Conclusions

Methane emissions from natural gas systems add significantly to regional methane emissions. Obtaining additional quantitative estimates of these emissions in Russian Federation requires additional financial and institutional support.

Table 3. Allocation of gas losses to the fundamental technological operations in the gas industry

Source of loss		Amount in % of total loss
Total		**100**
1.	**Production**	**20.79**
	— venting	17.82
	— fugitives	0.99
	— other	1.98
2.	**Transport**	**77.23**
2.1	Compression	47.77
	- start-stop venting	-
	- fugitives	8.17
	- other	-
2.2	Linear	29.46
	- venting	9.90
	- accident	2.48
	- fugitives	13.86
	- other	3.22
3.	**Processing**	**1.98**

Acknowledgements—I would like to thank a group of colleagues from Gazprom who assisted me in preparing this manuscript.

References

Gritsenko, A.I., 1993: 'Gas Resources of Russia'. Gazovaja Promyskleynost, N/O.

Rabchuk, V.I., Ilkevich, N.I., and *Kononov, Y.D.*, 1991: *A Study of Methane Leakage in the Soviet Natural Gas Supply System.* Siberian Energy Institute.

Werner Zittel, 1993: *Methane Emissions from Russian Gas Supply and Measures to Control Them* Ludwig-B'lkow-Systemtechnik GmbH, Daimlerstr. 15, D-85521 Ottobrunn.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Estimation of CO_2 Emission From Fossil Fuel Combustion in Russia: Progress and Problems

Sh. D. Fridman[1], **A. I. Nakhutin**[1], and **M. J. Shpirt**[2]

[1]*Institute of Global Climate and Ecology,*
20b Glebovskaya Street, 107258 Moscow, Russia
[2]*Institute of Fossil Fuel,*
29 Leninskiy Ave., 117910 Moscow, Russia

Abstract—Carbon dioxide emissions from fossil fuel combustion in Russia in 1990 were estimated as 2.49 gigatons (Gt) per year (or about 11 percent of global CO_2 emissions). Emissions from liquid fuels combustion were equal to 0.99 Gt (40 percent); solid fuels combustion — 0.59 Gt (24 percent); and natural gas combustion — 0.91 Gt (36 percent). Carbon dioxide emissions per gigajoule (GJ) of apparent fuel consumption were equal to 71.3 gigagrams (Gg) for liquid fuels, 90.4 Gg for solid fuels, and 53.2 Gg for natural gas; on average emissions were equal to 66.6 Gg of CO_2 per Gg of fossil fuel. The possibility of increasing the accuracy of CO_2 emissions estimates from solid fuels is discussed based on separate accounts of all classes of coal, coal burning in residential and commercial sectors, and coal dumps.

Key-words: CO_2 emissions and inventory, fossil fuel, coal, Russia.

1. Introduction

At present, the Russian Country Study team has collected sufficient data and established a database on various primary and secondary fossil fuels in a first attempt to estimate CO_2 emissions from energy use in Russia for 1990. Emissions were estimated in accordance with the IPCC methodology (*IPCC*, 1995).

2. Results and Discussion

2.1 CO_2 Emissions

Data on fossil fuel consumption in Russia in 1990 (according to official statistics) are shown in *Table 1*. These data are presented in units of 1,000 tons of equivalent fuel (tef) (coal equivalent). One ton of equivalent fuel equals 29.3 GJ.

Table 1. The 1990 balance of fossil fuels in Russia in 10^3 t of equivalent fuel (*Ministry* ..., 1994, *State* ..., 1994).

			Production	Imports	Exports	Internat Bunkers	Stock Change	Apparent Consumption
Liquid Fossil	Primary Fuels	Crude Oil	738343	70315	264343		-3987	548302
		Natural Gas Liquids						
	Secondary Fuels	Gasoline		1839	13956		-2116	-10001
		Jet Kerosene				1400		- 1400
		Other Kerosene		79	1909		- 45	-1785
		Gas/Diesel Oil		1418	28651		- 245	-26988
		Residual Fuel Oil		2441	33870		+ 468	-31897
		LPG		921	3913		-1749	-1243
		Ethane						
		Naphtha						
		Bitumen		42	645		+ 7	-610
		Lubricants						
		Petroleum Coke		280	113		+ 63	104
		Refinery Feedstocks						
		Naval Oil		159	4741		- 175	-4407
		Other Oil						
Liquid Fossil Totals			**738343**					**470075**
Solid Fossil	Primary fuels	Anthracite	107022	3727	25024		-2197	87922
		Coking Coal	65115	7136	22800		- 579	50030
		Other bit. Coal						
		Sub-bit. Coal	24560	139	3175		- 375	21899
		Lignite	64698		5328		- 93	59463
		Peat	1851	1	152		- 370	2070
	Secondary fuels	BKB & Patent Fuel		49	320		- 74	-197
		Coke		3698	2591		- 204	1311
Solid Fossil Totals			**263246**					**222498**
Gaseous Fossil		Natural gas (dry)	**737488**	106159	250414		+5889	**587344**
Total			**1739077**					**1279917**

It is noteworthy that the amount of exported fuel products is quite high. The ratio of export to production is 35.8 percent for crude oil, 34.0 percent for natural gas, and 22.6 percent for solid fossil fuels. As for secondary solid and liquid fossil fuels, their exports are up to ten times greater than imports.

In Table 1, exports and imports are considered for both the Commonwealth of Independent States (CIS) and for Baltic countries that were members of the former USSR in 1990.

CO_2 emissions from fossil fuel are calculated using carbon emission factors (*Table* 2) and the of amount carbon stored (*Table 3*). Results of calculations are presented in *Table 4*. It was concluded that total emissions were equal to 2.49 Gt of CO_2. Emissions from liquid fuel combustion were 0.99 Gt, or 40 percent; emissions from solid fossil combustion were 0.59 Gt, or 24 percent; and those from natural gas combustion were 0.91 Gt, or 36 percent.

To calculate emissions from coal, investigators cross-referenced classes of coal adopted in Russia and those described by the *IPCC* (1995) (*Fig. 1*). The IPCC classifies coals as lignite, sub-bituminous coal, coking coal, bituminous coal, and anthracite. At the same time, in Russian statistical publications coal is divided into two classes (coal used for power generation, and coking coal), into three classes (brown coal, black coal, and anthracite), or into 10 to 14 classes depending on the coal basin. In practice, each basin in Russia uses its own industrial classification. The coal of the same class from different basins can differ in its composition and properties, such as in its coking properties. The detailed coal classification includes the following classes: brown coal, long-flame coal, long-flame gas coal, gas coal, gas-fat coal, coking coal, coking-fat coal, coking coal-2, fat coal, lean-coking coal, badly coking coal, lean coal, half-anthracite coal, and anthracite coal.

The basis of the *IPCC* (1995) classification is the USA classification (ASTM D388–64) with the addition of coking coal, that is, the coal used for coke production. Only two parameters of this classification coincide with those of Russian industrial classification (the yield of volatile material and the coking ability). Consequently, additional data characterizing the caloric value of different coal ranks are used to compare the classifications. They are available from reference books on coal usage for power generation (*Energy...*, 1979; *Heat...*, 1973).

According to our estimates, the 1990 CO_2 emissions from fossil fuel combustion in Russia are equal to about 11 percent of corresponding global emissions estimated in the *IPCC* (1995), while the total population of Russia was only about 2.8 per cent of the global population in 1990.

Data from Tables 1 and 4 were used to calculate the amount of carbon dioxide produced per gigajoule of apparent fuel consumption (emission factor). For the apparent consumption of liquid fossil fuel this amount is equal to 71.3 Gg CO_2; for solid fossil fuel — to 90.4 Gg CO_2; for natural gas — to 53.2 Gg CO_2. On average, emissions were equal to 66.6 Gg of CO_2 per Gg of fossil fuel

Table 2. The values of factors and coefficients used for calculating CO_2 emissions in Russia.

			Conversion Factor (TJ/Unit)	Carbon Emission Factor (t C/TJ)	Fraction of Carbon Oxidized
Fuel Types					
Liquid Fossil	Primary Fuels	Crude Oil	29.3	20.0	0.99
		Natural Gas Liquids		17.2	0.99
	Secondary Fuels	Gasoline		18.9	0.99
		Jet Kerosene		19.5	0.99
		Other Kerosene		19.6	0.99
		Gas/Diesel Oil		20.2	0.99
		Residual Fuel Oil		21.1	0.99
		LPG		17.2	0.99
		Ethane		16.8	0.99
		Naphtha		(20.0)	0.99
		Bitumen		22.0	0.99
		Lubricants		(20.0)	0.99
		Petroleum Coke		27.5	0.99
		Refinery Feedstocks		(20.0)	0.99
		Other Oil		(20.0)	0.99
Liquid Fossil Totals			29.3		
Solid Fossil	Primary fuels	Anthracite	29.3	26.8	0.85
		Coking Coal		25.8	0.96
		Other bit. Coal		25.8	
		Sub-bit. Coal		26.2	0.97
		Lignite		27.6	0.98
		Peat		28.9	0.98
	Secondary fuels	BKB & Patent Fuel		(25.8)	
		Coke		29.5	
Solid Fossil Totals			29.3		
Gaseous Fossil		Natural gas (dry)	29.3	15.3	0.995
Total			29.3		

Table 3. 1990 estimates of carbon stored in Russia.

		Estimated fuel Quantities (*Ministry*, 1994, *State*, 1994)	Conversion Factor (TJ/Unit)	Carbon Emission Factor (t C/TJ)	Fraction of Carbon Stored	Carbon Stored (Tg C)
Fuel Types						
Naphtha		12437	29.3	(20.0)	0.80	5.82
Lubricants		6465	29.3	(20.0)	0.50	1.89
Bitumen		15266	29.3	22.0	1.00	9.83
Natural Gas		86444	29.3	15.3	0.33	12.79
Gas/Diesel Oil		460	29.3	20.2	0.50	0.14
LPG		4373	29.3	17.2	0.80	1.76
Other Fuels	Oil, distilled at the place of production	764	29.3	17.2	0.80	0.30
	Petroleum Coke	947	29.3	22.0	1.00	0.61

consumption. The estimated emission factors are useful for rough estimates of CO_2 emissions. Strictly speaking, the factors obtained in such a way do not take into account stored carbon, and this amount is included in the apparent consumption. However this error appears to be insignificant because the amount of carbon stored in Russia is less than 5 percent of the total carbon in liquid, solid, and gaseous fossil fuels (Tables 3 and 4).

Table 4. The 1990 CO_2 emissions from fossil fuel combustion in Russia

	Fraction of Carbon Oxidized	Actual Carbon Emission (Tg C)	Actual Carbon Emission (Tg C)
Crude Oil	0.99	317.00	1165.00
Gasoline	0.99	-5.48	-20.08
Jet Kerosene	0.99	-0.79	-2.90
Other Kerosene	0.99	-1.01	-3.70
Gas/Diesel Oil	0.99	-15.57	-57.08
Residual Fuel Oil	0.99	-19.50	-71.48
LPG	0.99	-2.35	-8.61
Bitumen	0.99	-0.38	-1.39
Petroleum Coke	0.99	-0.52	-1.90
Naval Oil	0.99	-2.55	-9.35
Liquid Fossil Totals			*989.40*
Anthracite	0.85	58.67	215.10
Coking Coal	0.96	36.30	133.10
Sub-bit. Coal	0.97	16.32	59.80
Lignite	0.98	47.10	172.70
Peat	0.98	1.72	6.30
BKB & Patent Fuel	(0.98)	-0.13	-0.48
Coke	(0.98)	1.09	4.00
Solid Fossil Totals			*590.50*
Natural gas (dry)	0.995	249.20	913.60
Total			**2493.50**

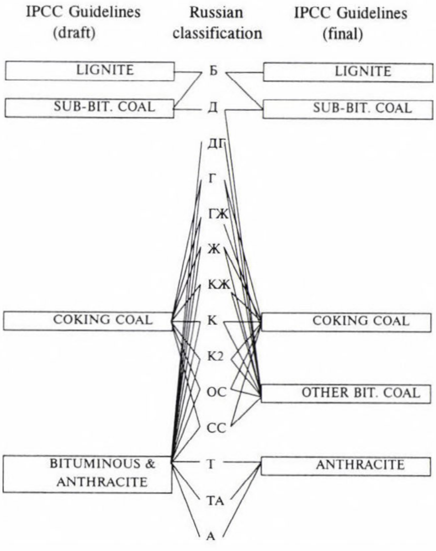


Fig. 1. Correlation between the Russian and IPCC classification of coals.

2.2 Means to Increase the Accuracy of Estimating CO_2 Emissions

A. Differentiated accounting for all classes of coal

To calculate CO_2 emissions, data on carbon content in coal or values of energy content per unit of mass are required. Following the techniques of official statistical reports, the conversion factor (Q_i /7,000, where Q_i is the caloric value for the *i*-th class of coal) is considered to be the same for all coal ranks within a certain basin. Such an approach can result in considerable error. For example, in 1990 in the Kuzbass basin, one of the greatest coal basins of Russia, 134.6 megatons (Mt) of coal were mined, including 16.05 Mt of coking coal (K), 80.933 Mt of coking-fat coal, 11.8 Mt of fat coal, 3.4 Mt of lean-coking coal, 28.6 Mt of badly coking coal, 38.5 Mt of gas coal, 12.2 Mt of long-flame coal, 21.03 Mt of lean coal, 1.18 Mt of gas-fat coal, and 0.86 Mt of anthracite. All of these coal types have different net caloric values (Q_i) .

Hence, for the Kuzbass coal, the weighted-averaged factor (based on the production values for each type), is equal to

$$\frac{Q}{7{,}000} = \frac{\sum_i \left[\left(\frac{Q_i}{7{,}000} \right) \times P_i \right]}{\sum_i P_i}. \tag{1}$$

The value calculated using Eq. (1) is equal to 0.77, while the official value is 0.86. Because official data were used for our calculations (in tef, see Table 1), the error of calculating CO_2 emission from Kuzbass coal can reach 12 percent. To increase the accuracy of the estimates, we are planning to carry out our calculations on the regional level (within certain basins), taking into account the carbon content and the heat of combustion for each coal type mined within each basin.

B. Accounting for coal enrichment

All coking coals and some coals used for generating electricity are enriched (this fact is not considered in the *IPCC,* 1995). In 1990 about 395 Mt of coal was produced, and about 200 Mt of it was enriched, including 110 Mt of coking coal.

The wastes after enrichment comprise from 25 to 35 percent of the initial coal mass. They contain from 4 to 20 percent of carbon implied in the coal before enrichment. This carbon should be considered as stored carbon. The *IPCC* (1995) does not take this factor into account.

In Russia, the amount of carbon in enrichment wastes can be estimated most completely by making estimates for individual regions, because local conditions influence the correlation between carbon content in wastes and in enriched coal. We are planning to carry out this work in the future.

C. Estimating the fraction of oxidized carbon

For anthracite, a comparatively low fraction of carbon oxidized, 0.85 (Table 2), was used in the calculations presented in the first section of this article. It reflects both relatively high losses by the incomplete burning of some part of the steam coal (lean coals and anthracites), and also carbon losses with enrichment wastes. Future attempts to calculate CO_2 emission will consider carbon in enrichment wastes as carbon stored. Hence, the fraction of carbon oxidized will increase slightly, reflecting only incomplete burning.

The fractions of oxidized carbon proposed by the *IPCC* (1995) (Table 2) reflect fuel burning conditions in industrial boilers. However, in Russia about 70 Mt of coal per year is used in residential and commercial sectors, that is, for burning in furnace systems. Such use causes greater fuel loss, which can reach from 6 to 11 percent even for sub-bituminous and bituminous coals.

The fractions to be considered will include the following: for lignite — 0.90–0.95; for sub-bituminous and bituminous coal — 0.89–0.94; and for anthracite — 0.83-0.86. The greater values correspond to grade coal, and the lesser to crushed coal (*Heat...,* 1973; author's own experimental data).

D. CO_2 emissions from the burning of coal dumps

Spontaneous burning is observed at 72 Russian dumps, which belong to coal-producing enterprises. These dumps contain about 700 Mt of coal rocks, with carbon content reaching 10%. Two hundred megatons of such rocks are stored every year. On average dumps are burning for 5–15 years. During this burning the fraction of carbon oxidized does not exceed 0.4–0.5, meaning that 5 Mt of CO_2 are emitted annually to the atmosphere. This estimate is approximate, and it will be refined in future studies.

3. Problems to be Solved

Several problems concerning the inventory of CO_2 emissions for fossil fuel combustion in Russia remain unsolved.

The first problem concerns estimates of bunker fuel consumption by marine transport, as well as estimating emissions that result from international transport by sea. Unfortunately, state and departmental statistics (both in the former USSR and in Russia) did not distinguish (and have not distinguished up to now) the fuel used for international transportation from the total amount of fuel used by the marine transport. Perhaps this problem can be solved with the help of indirect and expert estimations, such as using data on the amount of cargo transported.

An attempt to estimate bunker fuel consumption by international air transport was successful; the results are shown in Table 1.

The second problem is that of primary and secondary fossil fuel losses during transporting, storage, processing, and consumption. Carbon contained in lost fuel should be considered as stored carbon, such as concerns the oil and oil products losses resulting from pipeline accidents. However, in some cases, oil collected during liquidation of the accidents is burned, resulting in the emission of CO_2 and other greenhouse gases. The situation is the same when accidents occur on the gas pipelines; some accidents are accompanied by gas flaring.

In our opinion, the available estimates of primary and secondary fossil fuel losses in Russia cannot be considered complete and reliable. The estimated accidental oil losses from pipelines are equal to 1.2 percent of extracted oil (*Yablokov,* 1995). The upper limit of gas leakage from cross-country gas pipelines is estimated in *Fridman* and *Nakhutin* (1995). Progress in solving this problem will decrease the uncertainty in CO_2 emissions estimates.

There is one additional problem not yet solved. Its nature is political rather than technical. In 1990, considerable military contingents of the former USSR were located beyond the borders of the country. Apparently, the fuel they consumed was delivered from the USSR and not purchased at these places. Corresponding emissions of CO_2 and other greenhouse gases took place beyond the borders of the USSR. Sometime after 1990 all of these military contingents became a part of the Russian Army and were brought back to the Russian territory. It is not clear whether emissions from the mentioned military contingents should be distributed among the Commonwealth of Independent

States and Baltic countries, or whether it should be considered as a part of Russian emissions. The third option to consider in treating these emissions is to not add them to emissions of any individual country (similar to emissions from bunker fuel).

4. Conclusion

Carbon dioxide emissions from combustion of all types of fossil fuels were estimated using the IPCC methodology. Total 1990 emissions in Russia were equal to 2.49 Gt CO_2, or about 11 percent of global emissions, including 0.99 Gt CO_2 from liquid fuels, 0.59 Gt CO_2 from solid fuels, and 0.91 Gt CO_2 from natural gas.

In our opinion, the means to increase the accuracy of estimating Russia's emissions may include differentiating the classes of coal produced at every coal basin of the country, accounting for coal enrichment wastes as carbon stored, and accounting for emissions from burning coal dumps. Some country-specific values of the fraction of carbon oxidized may also be used to improve estimates of emissions from solid fuels.

The following actions need to be taken to improve the estimates of Russia's CO_2 emissions:

— search for data on direct or indirect bunker fuel consumption by international marine transport;

— estimate the losses of primary and secondary fuel;

— estimate directly or indirectly the CO_2 emissions from military activity beyond the borders of the country;

Estimating and summarizing the net errors and the total uncertainty of emissions is the problem that we hope to solve in the near future. We will also try to improve estimates of CO_2 emissions from energy and the other sources.

Acknowledgements—The authors are very grateful to *Dr. V.P. Antonov, Dr. V.I. Kopytin* and *Dr. V.A. Nikolsky* for assistance in obtaining and interpreting statistical data and to *O.V. Glushko* and *T.V. Grigurina* for technical assistance in the preparation of this article.

References

Energy Fuel of the USSR, 1979: Energy (in Russian), Moscow.

Fridman, Sh.D. and *Nakhutin, A.I.*, 1995: Overview of anthropogenic methane emissions in Russia (1990-1994). *Időjárás,* this issue.

Heat Design of Boiler Equipment, 1973: Energy (in Russian), Moscow.

IPCC, 1955: Guidelines for National Greenhouse Gas Inventories, 1-3, UNEP/OECD/IEA/IPCC.

Ministry of Fuel and Power of Russian Federation (Mintopenergo), 1994.

State Committee of Russian Federation on Statistics (Goscomstat), 1994.

Yablokov A., 1995. *Izvestiya* N°. 22, 1 (in Russian).

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Overview of Anthropogenic Methane Emissions in Russia (1990–1994)

Sh. D. Fridman and **A. I. Nakhutin**

Institute of Global Climate and Ecology,
20b Glebovskaya Street, 107258 Moscow, Russia

Abstract—Anthropogenic emissions of methane in Russia were estimated by source, using published data and the authors' own calculations, mostly based on the IPCC methodology. In a preliminary estimate, total 1990 emissions, amounted to 27.4 million metric tons of methane. Natural and oil gas production and transportation are the most important sources of emissions in Russia (16.0 million metric tons of methane), but such emissions are the least accurately quantified. Domestic animals are the second largest source of methane (4.9 million metric tons, including animal wastes), and landfills are the third. Russia contributes approximately 7 percent of global anthropogenic emissions. The structure of Russian emissions differs from the global pattern; most of its methane is emitted during fossil fuel production, while the fraction of methane from rice paddies is very small. Total methane emissions decreased from 1990 to 1994 because of the crisis in national industry and agriculture. This decrease covered all emissions sources except solid wastes, which grew because of methane generation by wastes that were landfilled from 1970 to 1990, when the amount of wastes increased linearly with time.

Key-words: methane emissions and inventory, natural and oil gas, enteric fermentation, landfills, coal, oil, animal wastes, Russia.

1. Introduction

There are at least two major objectives of estimating anthropogenic methane emissions in Russia (beyond formally fulfilling Russia's obligations within the United Nations Framework Convention on Climate Change). First, the anthropogenic methane emissions in Russia are obviously a significant part of global emissions. Second, the decrease in methane emissions in countries with economies in transition (including Russia) is considered to be one possible cause of the decreasing atmospheric methane concentration. Observed in recent years, the decrease ranged from about 1.2 percent per year in the late 1970s to about 0.3 percent per year in 1992 (*IPCC,* 1992; *Khalil* and *Rasmussen,* 1993; *Prinn,* 1994). We hope that estimating the anthropogenic methane emissions in Russia in 1990–1994 will help us better understand the methane balance in the atmosphere.

According to previously completed studies, anthropogenic methane emissions in the USSR from 1987 to 1990 ranged between 19 to 34 million metric tons per year (*Izrael et al.*, 1993 and 1994; *Nazarov et al.*, 1992; *Subak et al.*, 1993; *Bashmakov et al.*, 1990; and *World Resources*, 1992).

2. Methane Emissions in 1990

The main source of methane emissions in Russia is gas production, transportation, storage, and distribution. The majority of uncertainty in estimating emissions is caused by the lack of reliable statistical data and appropriate emission factors. In *Fig. 1*, gas fluxes in the Russian economy are shown as well as the types of emissions from each branch of the gas sector.

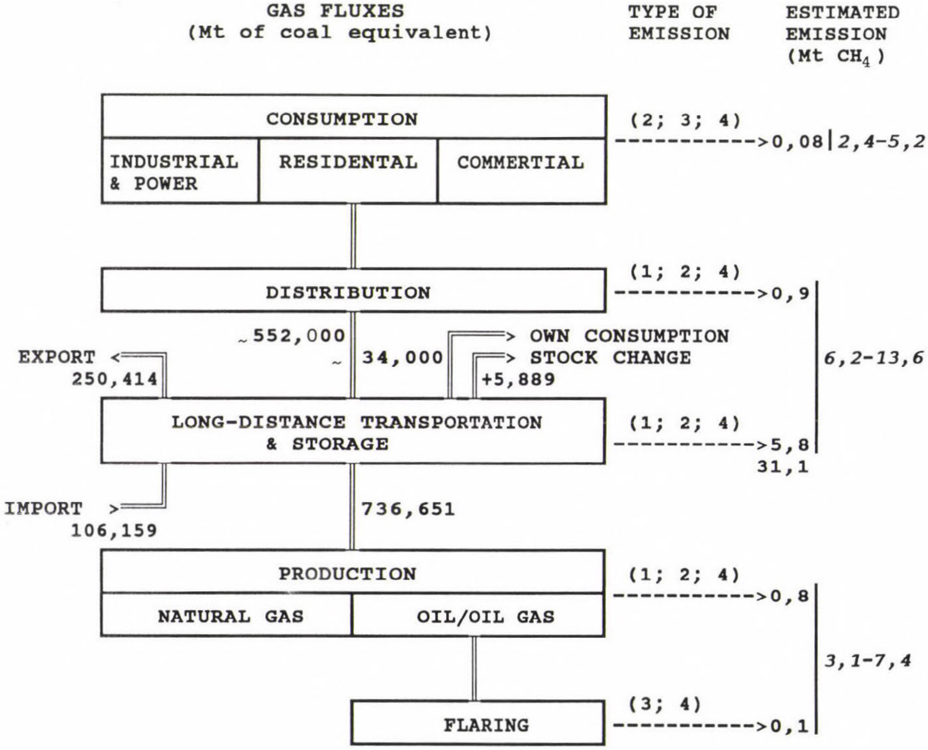


Fig. 1. Gas fluxes and CH_4 emissions in the Russian gas industry (1990); 1—technological emissions; 2—leaks; 3—accidents; 4—incomplete combustion. The IPCC estimates of emissions are given in italics.

The total emission is the sum of technological releases, leakage, releases from accidents, and methane releases resulting from the incomplete combustion of gas. The smallest (7.8 million metric tons of methane) emissions estimate in 1990 was obtained on the basis of data provided by the Institute of Energy Research (*Izrael*, 1993, 1994). This estimate was partially confirmed by the results of experiments carried out with the authors' participation at gas pipeline compression stations. Approximate estimates of medium- and low-pressure (0.9 million metric tons of methane) emissions from gas distribution systems was added to the above mentioned amount.

Using emission factors provided by the IPCC/OECD (*IPCC*, 1995) we obtained another total estimate of methane emissions equal to 11.8–26.3 million metric tons of methane. The third method of estimation was based on data from the joint-stock company 'Gasprom'. In 1991, 9.3 percent of extracted gas (46.1 million metric tons) was used for technological purposes (*Gritsenko,* 1993). At the same time, gas consumption by equipment used in the system of gas storage and transport, taking into account its capacity factor, was estimated as 15.5 million metric tons. The difference between the two estimates can be attributed to emissions in the atmosphere and illegal gas consumption (gas theft). So far, as there are no reliable estimates of illegal gas consumption in Russia, we can consider 31.1 million metric tons of methane as the upper limit of methane emission from the system of gas transport. This value is equal to (see *Fig. 2*) the difference between the official value of gas consumption within the gas system (46.1 million metric tons) and consumption estimated using the technology-specific consumption factors (15.5 million metric tons). When gas losses that occur in other parts of the gas system (i.e., production and distribution) were added to the losses from transmission, the total 1990 natural gas emissions in Russia were estimated as 32.9 million metric tons, or about 5 percent of the gas extracted. This value represents the upper limit of the emission range.

In *Table 1*, anthropogenic methane emissions from the main sources are shown for 1990. Emissions from the gas system were assumed to be equal to 16.0 million metric tonnes per year, the central estimate between the upper and lower (0.0) emission range limits.

Enteric fermentation is the second largest source of methane emissions in Russia. These emissions together with emissions from animal wastes amount to 4.9 million metric tons per year (*Izrael et al.,* 1993, 1994). This result was calculated using emission factors recommended by the IPCC (*IPCC*, 1995) for Eastern Europe (for enteric fermentation) and a cool climate (for animal wastes).

The third largest source of methane emissions in Russia is municipal solid wastes (MSW) in landfills, amounting to 2.4 million metric tons of methane per year (*Izrael et al.,* 1993, 1994). This estimate is based on an emission factor equal to 0.086 ton of methane per ton of MSW and an MSW generation rate equal to 0.8 kilogram per person per day for urban populations (*Guidebook...*, 1993). Urban population figures for 1980 were used for the calculation, because according to available data, methane emissions from waste peak about 10–12 years after the MSW is landfilled (*Nazarov et al.*, 1991).

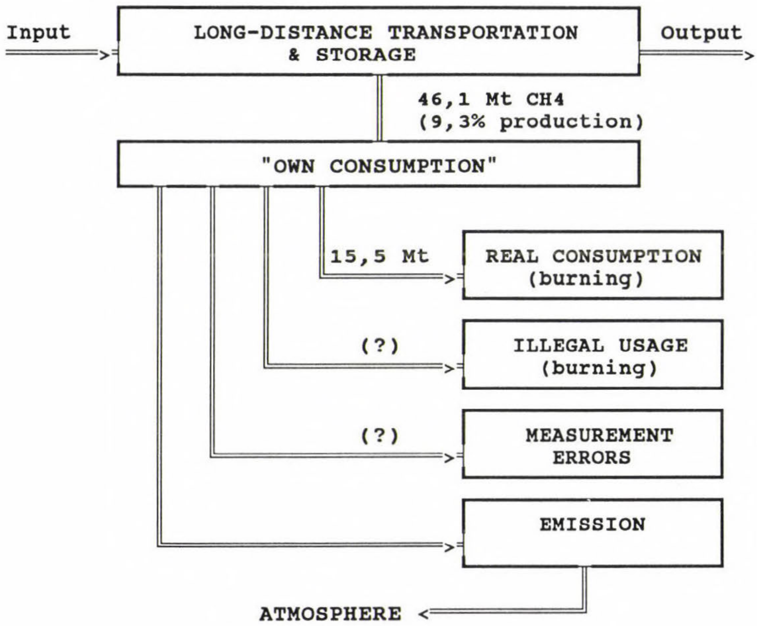


Fig. 2. Scheme of estimating anthropogenic CH_4 emission from gas transportation and storage.

Additional important sources of methane, included in Table 1, are coal mining and oil extraction. Estimates of methane emissions from these sources have been published by *Izrael et al.* (1993, 1994), *Nazarov et al.* (1992), and *Vekilov et al.* (1991, 1992). Unfortunately, these estimates do not take into account methane released by the transportation, storage, and processing of oil.

Rice production is not well developed in Russia and its contribution to methane emissions is not significant (Table 1). Thus, the total emissions of methane in Russia in 1990 can be estimated as 27.8 million metric tons of methane, which in the following discussion, we will call the 'the most probable' estimate. In reality, this value can be larger because the following emissions should be added to those mentioned above: emissions from incomplete combustion of fossil fuel and emissions from biomass combustion. However, it is expected, that emissions from these two sources are not significant.

Table 1. Stucture of anthropogenic methane emissions

Emission source	Emissions (%)		
	World (*IPCC*, 1994)	Russia	Former USSR (*Nazarov et al.*, 1992)
Fossil fuel	28	72	63
Enteric fermentation	22	16	27
Animal wastes	7	2	N/A
Rice paddies	17	0.4	1
Biomass burning	11	(?)	3
Landfills	8	9	6
Wastewater	7	1(?)	N/A
Total	**100**	**100**	**100**

Izrael et al. (1993, 1994) estimated methane emissions from non-agricultural biomass burning, mainly from forest fires, to be 0.8 million metric tons per year. Based on our evaluation, this estimate should be reduced to 0.5 million metric tons per year when more realistic emission factors are used.

Methane emissions from liquid wastes in Russia are estimated as 0.4 million metric tons of methane per year (*Abramov et al.,* 1992).

Table 2 and *Fig. 3* illustrate the role of different sources in the total structure of methane emission in Russia, in the former Soviet Union, and at a global scale. It appears that the structure of emissions in Russia resembles that of the Soviet Union, with fugitive emissions playing the leading role. The importance of fugitive emissions in Russia was found to be even greater, because the main Soviet Union oil and gas production sites were located on Russian territory. Otherwise, the contribution of enteric fermentation and animal wastes is somewhat less in Russia than in the former Soviet Union.

Table 2. Antropogenic methane emission in Russia in 1990

Emission source	Emissions (Mt CH_4)
Natural + oil gas	16.0 (7.8–32.9)[1]
Enteric fermentation	4.4
Landfills	2.4
Coal	1.9
Oil	1.9
Animal wastes	0.5
Rice paddies	0.1
Wastewater	0.4(?)
Total	**27.3**

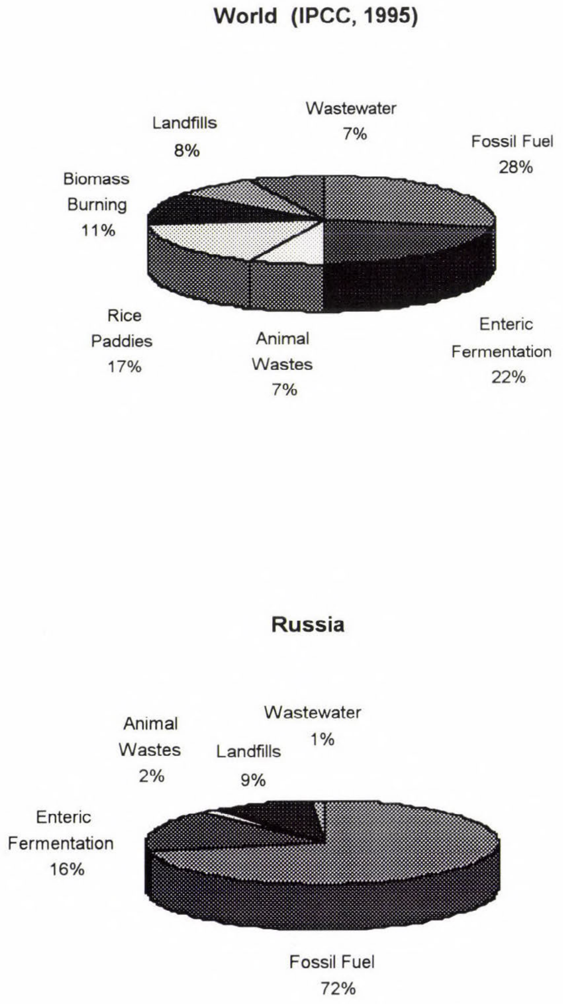


Fig. 3. Structure of anthropogenic methane emissions in Russia, in comparison with the structure of global emissions.

Comparing the structure of global emissions with the structure of emissions in Russia shows that the role of emissions from fossil fuels is much greater in Russia, and the contribution of rice production is insignificant compared to global methane emissions.

Russian contribution to global anthropogenic methane emissions is illustrated in *Table 3*. As one can see, Russia's share is highly significant for emissions from fossil fuels and from solid and animal wastes, but is quite insignificant for emissions from rice paddies.

Table 3. Russia's contribution to global methane emissions

Emission source	Global emissions ($Mt\ CH_4$) (*IPCC*, 1994)	Russia's contribution (%)
Fossil fuel	100	19.6
Enteric fermentation	80	5.5
Rice paddies	60	0.2
Biomass burning	40	(?)
Landfills	30	8.0
Wastewater	25	1.6(?)
Aminal wastes	25	2.0
Total	**360**	**7.7**

3. Emissions from 1990 to 1994

The first half of the 1990s was a period of economic crisis that extended to all sectors of the Russian economy and affected almost all major sources of methane emissions. The amounts of emissions calculated by the authors for 1990–1994 are presented in *Table 4* (an initial version of this calculation was first presented by *Izrael et al.* (1993, 1994). The most notable decreases were observed for emissions from coal, 32 percent, and oil, 42 percent, as shown in *Fig. 4.* The increase of emissions from solid wastes shown in Table 4 was connected with a linear increase in the amount of wastes put in landfills from 1970 to 1990 (*Abramov et al.,* 1992). On average, methane emissions from the landfilled municipal solid waste (MSW) reach maximum after 10–12 years (*IPCC,* 1995; *Nazarov et al.,* 1991).

Table 4. Methane emissions in Russia in 1990–1994

Emission source	Emissions ($Mt\ CH_4$)				
	1990	1991	1992	1993	1994
Natural & oil gas	16.0	16.1	16.1	15.5	15.2
Enteric fermentation	4.4	4.2	4.0	3.8	3.4
Landfills	2.4	2.5	2.5	2.6	2.6
Coal	1.9	1.7	1.6	1.5	1.3
Oil	1.7	1.5	1.3	1.2	1.0
Animal wastes	0.5	0.5	0.4	0.4	0.4
Rice paddies	0.1	0.1	0.1	0.1	0.1
Wastewater	0.4(?)	0.4(?)	0.4(?)	0.4(?)	0.4(?)
Total	**27.3**	**27.0**	**26.4**	**25.5**	**24.3**

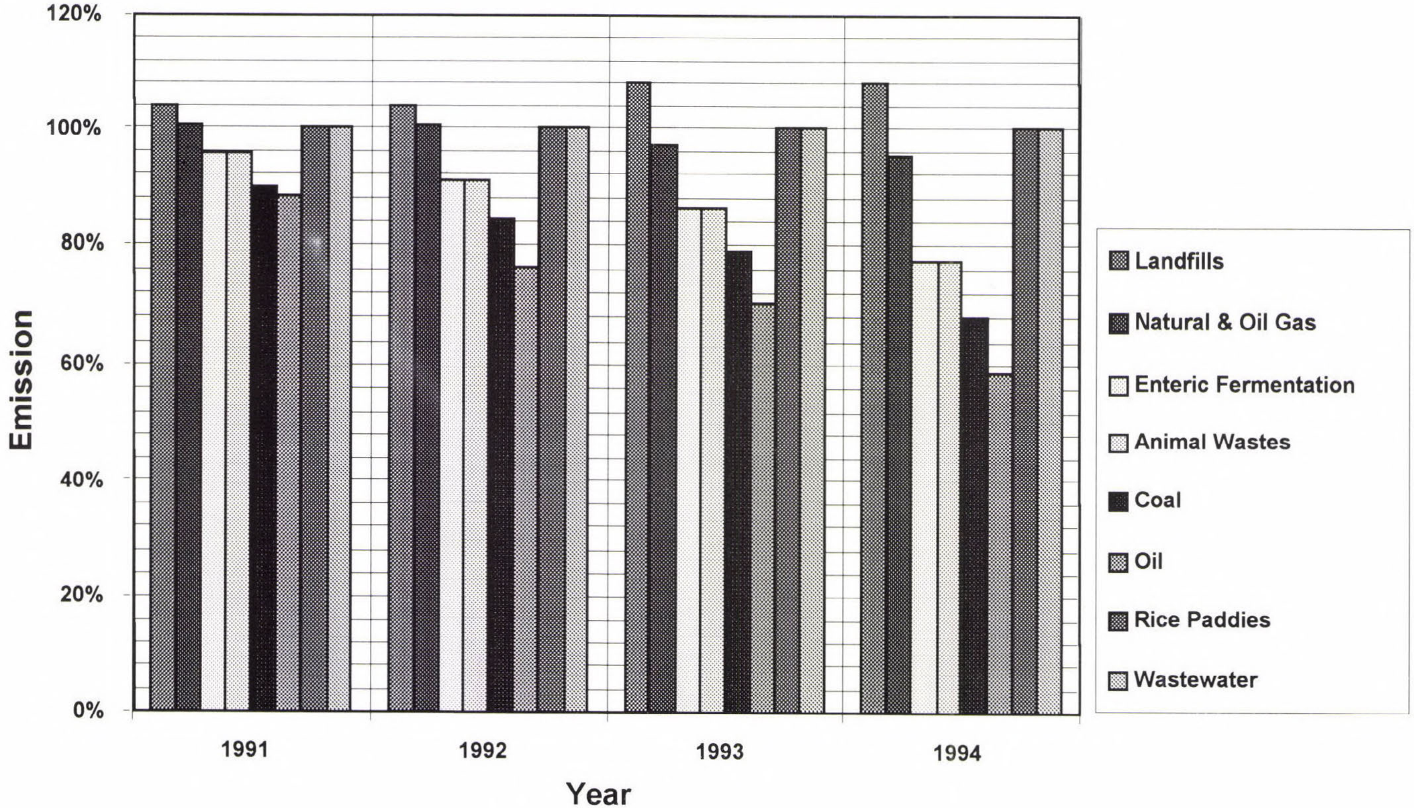


Fig. 4. Methane emissions in Russia in 1990-1994.

It is noteworthy that the 1991–1994 results shown in Table 4 were obtained on the basis of national statistics describing such economic parameters as fossil fuel production or the number of animals. Emission factors were considered to be the same as in 1990. In reality, such a suggestion is not entirely accurate. For example, in the oil and gas industry in conditions of economic crisis, ageing and worn equipment was not replaced in time, resulting in an increase in the number of technological and accidental gas losses to the atmosphere. On the other hand, changes in economic conditions made producers and consumers pay more attention to preventing gas leaks. In the livestock sector, the increase in fuel prices resulted, in some cases, in the refusal to use animal wastes as a fertiliser, thus increasing the period of its storage in anaerobic conditions. This can lead to an increase in the corresponding methane emission factor.

Change in the emission factor was also reported for liquid wastes. In particular, in Moscow a considerable decrease in methane emissions from wastewater treatment was observed. This was caused by the change in the organic matter content of liquid wastes, which resulted from economic recession (*Nedogonov,* 1995).

The decrease in total methane emissions to the atmosphere in Russia in 1994 was equal to 3 million metric tons per year, or 11 percent as compared with 1990 (according to the 'most probable' scenario). Methane emissions from the gas system according to the 'minimal', 'maximal', and the 'most probable' scenarios are shown in *Fig. 5*.

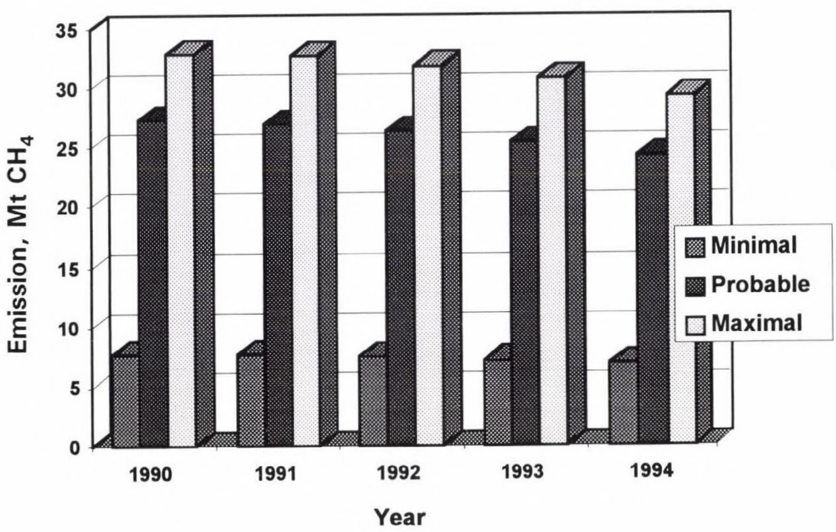


Fig. 5. The 'minimal', 'maximal' and the 'most probable' scenarios of emissions from the gas sector in 1990–1994.

In 1993, the emissions decrease was equal to 7 percent as compared with 1990. It is noteworthy that recession in industry for this period was 37 percent (*Recession...,* 1994a; *Redundant...,* 1994). Thus the decrease in methane emissions was considerably lower than the rates of industrial recession.

In addition to such factors as growing emissions from solid wastes (Table 4), this delay may have several causes (*Recession...,* 1994a; *Recession...,* 1994b). First, in the early 1990s Russia experienced a general increase in energy consumption per unit of production leading to an increase in fossil fuel consumption per unit of production. Second, the oil and gas production sectors of the economy, the major sources of methane emissions, exported abroad a considerable part of their output. As a result, they suffered much less from the economic crisis than other sectors of the economy. Finally, official statistics tend to overestimate the real value of the recession in industry because a large number of non-state enterprises do not report part of their revenues to evade taxation (*Recession...,* 1994a; *Recession...,* 1994b; *Redundant...* 1994).

Over the course of the 20th century the structure of methane emissions in Russia experienced significant changes (*Table 5*) (*USSR...,*. 1987; *Melentyev,* 1987; *Probst,* 1939). Methane emissions from landfills were estimated using emission factors recommended for developing countries (*IPCC,* 1995). Emission factors for coalbed methane were considered to remain constant and equal to those used in 1990 inventory. During the investigated period natural gas was not produced in Russia, so the corresponding emissions were equal to zero. Data on methane emissions from animals and animal wastes were obtained from *Nazarov et al.,* 1992. It was also assumed that from 50 to 100% of produced oil gas is released in the atmosphere.

Table 5. Methane emissions in Russia in 1913–1917

Emission source	Activity			Emissions
	Primary data	Measurement units	Value	(Mt CH_4)
Enteric fermentation				3.2
Animal wastes				0.4
Solid wastes	Urban population	10^6 persons	29.1	0.3
Oil	Production	10^6 t coal equivalent	11.7	0.2–0.5
Coal	Production	10^6 t coal equivalent	29.0	0.2
Gas	Production		0.0	0.0
Total				**4.3–4.6**

Results presented in Table 5 include emissions from both the territory of Russia in its present borders, and from the territories of all countries of the Commonwealth of Independent States and the Baltic States.

4. Conclusions

Total 1990 anthropogenic methane emissions in the Russian Federation are estimated as 27.4 million metric tons of methane. The most important source of methane emissions was natural and oil gas production, transportation, storage, distribution, and consumption, including sufficient amounts of gas produced for export. Emissions in the gas sector were estimated to range from 7.8 to 32.9 million metric tons of methane, 16.0 million metric tons being the most probable value. Livestock was the second largest source with 4.9 million metric tons of methane in 1990. Municipal solid wastes in landfills were in third place.

Russian contribution to global anthropogenic emissions of methane was estimated as approximately 7 percent.

The structure of Russian emissions by source differs significantly from the global structure. Most emissions (72 percent) are fugitive emissions from oil and gas systems, while emissions from rice paddies are quite insignificant.

Total methane emissions decreased during 1990–1994 because of the economic crisis; total emissions in 1993 were 7 percent less than in 1990, while the decrease in industrial activity was 37 percent. The most notable decreases were observed for emissions from coal (32 percent) and oil (42 percent). Emissions from solid wastes increased because of the increase in landfilled waste in 1970–1990 and the 10–12-year time lag between landfilling and the maximum methane release.

Methane emissions in Russia from 1913 to 1917 were estimated as 4.3–4.6 million metric tons, with livestock being the major emission source.

Acknowledgements—The authors thank *L.O. Volkov* who carried out the calculations of emissions from animals and animal wastes, as well as *O.V. Glushko* and *T.V. Grigurina* who rendered essential assistance in preparing this report.

References

Abramov, N.F., Suvorov, V.N., Borisov, Yu.A., et al., 1992: *Estimation and Comparative Analyses of the Intensity of Anthropogenic Methane Emission from the Disposal of Solid and Liquid Wastes on the Territory of Russia* (Report) (in Russian). Academy of Municipal Economy, Moscow.

Bashmakov, I.A., Beschinskiy, A.A., Bogoslovskaya, N.N., et al., 1990: *Strategy for Estimating Opportunities to Lower Greenhouse Gases Emission from USSR Energetics* (Report, in Russian). Institute of Energy Research. Moscow.

Gritsenko, A.I., 1993: 'Gas Resourses of Russia' (in Russian). Gazovaya Promyshlennost, Number 10, pp. 19–21.

Guidebook of the Maximum Permissible Concentrations of Harmful Substances in Foodstuff and the Environment, 1993 (in Russian). Moscow.

IPCC, 1992: Climate Change: The Supplementary Report to the IPCC Scientific Assessment (eds.: *J.T. Houghton, B.A. Callender,* and *S.K. Varney*). Cambridge University Press, Cambridge, UK.

IPCC, 1994: *Radiative Forcing of Climate Change*. WMO-UNEP. Cambridge University Press, Cambridge, UK.

IPCC, 1995: *Guidelines for National Greenhouse Gas Inventories. Vol. 1-3*, UNEP/OECD/IEA/-IPCC.

Izrael, Yu.A., Nazarov, I.M., Yakovlev, A.F. et al. 1993, 1994: *Inventory and the Cadastrial Estimation of Greenhouse Gases Anthropogenic Emissions in the Main Sectors of the Economy of the Russian Federation* (in Russian, Report). Institute of Global Climate and Ecology. Moscow.

Khalil, M.A.K. and *Rasmussen, R.A.*, 1993: Decreasing trend of methane: unpredictability of future concentrations. *Chemosphere 26*, 803–814.

Melentyev, L.A., 1987: *Sketches on the History of Home Energetics* (in Russian). Nauka, Moscow.

Nazarov, I.M., Fridman, Sh.D., Artemov, V.M. et al. 1991: *Inventory of Greenhouse Gases Sources and Sinks in the USSR* (in Russian) (Report). Institute of Global Climate and Ecology. Moscow.

Nazarov, I.M., Fridman, A.I., Fridman, Sh.D., et al., 1992: Anthropogenic emission of methane in the Commonwealth of Independent States and the Baltic States (in Russian). *Meteorologiya i Gidrologiya*, No. 11, 15–20.

Nedogonov, V., 1995: *Life in the Zone of Active Silt* (in Russian). Moscowskie Nowosti, No. 7, 23.

Nikolayev, A.N., Nakhutin, A.I., Vorobyev, V.A. et al., 1993: *Investigation of Content and Transformation of Pollutants in the Atmosphere near the Units of the Gas Transportation System* (in Russian, Report). Institute of Global Climate and Ecology, Moscow.

Prinn, R.G., 1994: Interactive atmosphere: global atmospheric-biospheric chemistry. *Ambio 23*, No. 1, 50–61.

Probst, A.E., 1939: *The Main Problems of Geographical Deployment of the Fuel Industry of the USSR* (in Russian). USSR Academy of Science, Moscow.

'Recession does not Permit Energy Saving', 1994a. *Finansovye Izvestiya*, No. 38, II (in Russian).

'Recession Results in Economic Normalization' 1994b. *Finansovuye Izvestiya*, No. 58, II (in Russian).

'Redundant Employment Becomes Dangerous for Market Economy" 1994. *Finansovuye Izvestiya*, No. 67, VIII (in Russian).

Subak, S., Raskin, P., and *von Hippel, D.*, 1993: *Climatic Change 25*, No. 1, 15–58.

USSR Economy for 70 Years, 1987. Finansy i Statistica, Moscow (in Russian).

Vekilov, E.H., Demidiuk, L.M., Dmitriev, A.M., et al., 1991, 1992: *Interpretation Report on the Preliminary Estimation of Greenhouse Gases Emission from the Units of Mining, Oil- and Gas-producing Industry, and the Comparative Estimation of Anthropogenic and Natural Emission on the Territory of the Russian Federation* (in Russian). 'Tehnorisk' Centre of Moscow State University. Moscow.

World Resourses, 1992. Oxford University Press. New York, Oxford.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Greenhouse Effect and Situation in Lithuania

B. Jaskelevicius[1], **V. Krusinskas**[2], and **A. Zukauskas**[2]

[1] *Lithuanian Academy of Sciences,*
Gedimino pr. 3, 2600 Vilnius, Lithuania

[2] *Environmental Protection Ministry of Lithuania,*
Juozapavi Piaus 9, 2600 Vilnius, Lithuania

Abstract—In 1990, Lithuania consumed 513 PJ of fossil fuels. Lithuanian energy and transportation sectors produced approximately 37 Tg of carbon dioxide in 1990 and 17 Tg in 1994. According to preliminary estimates, Lithuania's carbon dioxide emissions comprise only about 0.07 percent of global emissions.

Although national emissions during the last several years have declined, total pollution levels in Lithuania remained constant. According to the Lithuanian Institute of Physics estimates, in 1992–1993 sulphur and nitrogen oxide transport from neighbouring countries exceeded local emissions. Concern about the deterioration of air quality makes it necessary to assess transport of pollutants, including greenhouse gases, from abroad.

A National Program to reduce emissions should be based on a clear strategy incorporating energy production and industrial development. In all economic scenarios for Lithuania, the Ignalina Nuclear Power Plant (NPP) plays an extremely important role. In 1993 this plant produced about 87% of Lithuania's electricity. The unreliability of RBMK-type reactors and construction shortcomings of the first Ignalina NPP reactor are causes for serious concern, however, the shutdown of the NPP potentially planned for 2000 would cause a severe electricity deficit. To satisfy future energy demand, it was suggested that a coal fired power plant be built with similar capacity. If this plan is pursued, national emissions of carbon dioxide will increase by 30%, sulphur oxides emissions by 140%, and nitrogen oxides emissions by 50%. As a result, replacement of the nuclear plant with a coal fired plant is not a satisfactory solution. New strategies to address the power supply problem must be developed.

Key-words: Lithuania, GHG, emission, industry, energy, transport.

1. Fuel Consumption and Greenhouse Gas Emissions in Lithuania

The Republic of Lithuania has signed the United Nations Framework Convention on Climate Change, obligating a reduction in emissions of carbon dioxide and other greenhouse gases. In order to meet this obligation, an inventory of GHG emission sources and sinks in Lithuania must be compiled, and domestic measures to reduce the adverse effects of climate change should be evaluated. Below is a preliminary assessment of greenhouse gas emissions in Lithuania, as well as a description of major source activities.

The National Energy Efficiency Program developed in Lithuania in 1991 proposed energy-saving options in electricity generation and manufacturing sectors at the country level. The program was based on the assumption that energy consumption would increase over time. On the contrary, in 1990 to 1991 a considerable decline in energy consumption has occurred. This decline was not caused by energy savings or the introduction of reasonable consumption policies, but was instead due to reduced productivity, restriction on demand, and an abrupt increase in energy prices.

Iñ 1939, firewood and coal met 87 percent of the overall energy demand in Lithuania and households consumed about 72 percent of the total energy produced. Only 4 percent of total energy was generated by stand-alone power plants. After World War II, the fuel budget changed dramatically. Energy consumption reached its peak in 1990 and than declined abruptly in 1991 (*Fig. 1*).

It is important to note that locally produced fuels, including oil, firewood, peat, hydropower, and fuel from waste, satisfied only 2.5 percent and 5 percent of the total energy demanded in 1990 and 1993, respectively. Due to political and economic changes in the 1990s, the import of natural gas, which is ecologically the most pure fuel, was sharply reduced. In the last two years the consumption of oil was reduced twofold, natural gas fourfold, and coal threefold.

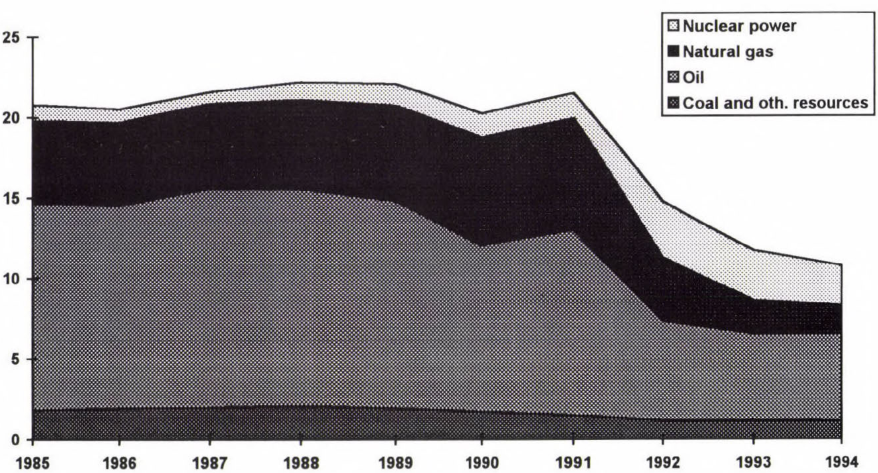


Fig. 1. Energy consumption in Lithuania (million tones of coal equivalent).

Carbon dioxide constitutes the largest amount of combustion emissions. Lithuanian energy and transportation sectors released approximately 37 Tg of carbon dioxide in 1990 and 17 Tg in 1994. Though in tree years CO_2 emissions in Lithuania were reduced almost by half, this reduction was caused by a decline in industrial output, rather than by special measures or technological advancement. On the global scale Lithuanian CO_2 emissions make up only about 0.07 percent of the global CO_2 emissions. Emissions of greenhouse gases and ozone precursors in Lithuania are shown in *Tables 1* and *2*, and *Figs. 2* and *3*.

Table 1. Emission of air pollutants from stationary sources in Lithuania in 1992 (Gg)

Branch of economy	Solid particles	Sulfur oxides	Nitrogen oxides	Carbon monoxide	Volatile organic substances
Industry	20.48	35.18	8.35	47.97	9.78
Electric utilities	0.69	35.44	6.49	2.99	0.002
Agriculture	0.35	1.53	0.42	1.16	0.02
Forestry	0.15	0.08	0.02	0.31	
Services	0.30	0.41	0.05	0.14	0.17
Construction	1.14	2.00	0.31	1.36	0.09
Households	1.49	17.48	3.27	4.60	0.05
Total	**24.60**	**92.12**	**18.91**	**58.53**	**10.11**

Table 2. Combustion-related emissions of greenhouse gases and ozone precursors in Lithuania in 1990

Greenhouse gas	Global warming potential (100 years)	Emission (Gg)	Emission in units of CO_2 (Gg)	%
Direct effect:				
CO_2	1	37,000	37,000	97
CH_4	24.5	31	760	2
N_2O	320	1	320	1
Indirect effect:				
CO	–	644	–	–
NO_x	–	178	–	–
Total			**38,080**	**100**

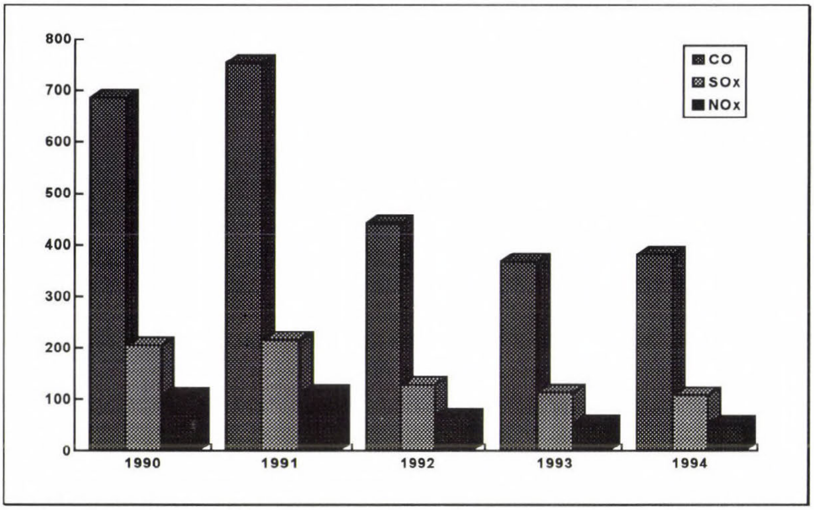


Fig. 2. Carbon monoxide, sulfur oxides and nitrogen oxides emissions from fuel combustion in Lithuania in 1990-1994 (Gg).

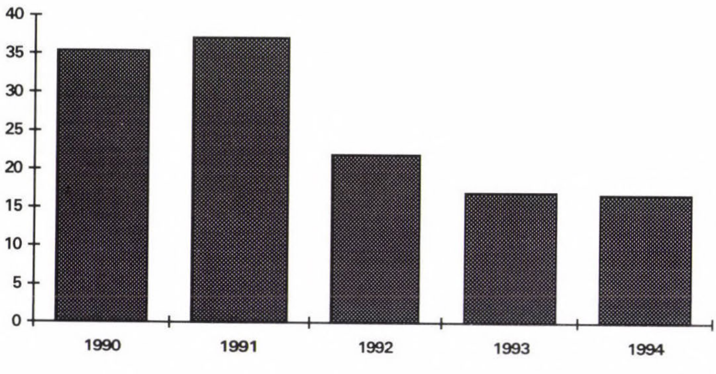


Fig. 3. Carbon dioxide emissions from combustion processes in Lithuania.

2. Air Pollution in Lithuania

Rates of air pollution are evaluated using measurements at stationary observation posts that are distributed throughout Lithuania. The continuing concentration of pollution sources in large towns and industrial centres in recent decades led to a dramatic increase in air pollution. The most important parameter for describing atmospheric quality in Lithuania is the maximum admissible concentration (MAC), or the maximum concentration of a substance in the atmosphere that causes no adverse effects on people and nature during a certain period of time. As suggested by data from the Lithuanian State Department of Environmental Protection and from the Lithuanian Energy Institute (*Burneikis,* 1993), in 1990, MACs were exceeded in one-third of the country. At the same time, 10 percent of the country's actual concentrations of pollutants were twice as large as corresponding MACs. The situation was most serious around such large towns and industrial centres as Vilnius, Elektrenai, Kaunas, Jonava, Kedainiai, Akmene, and Mazeikiai.

Studies by the Lithuanian Physics Institute and data published by the Lithuanian State Department of Environmental Protection indicate that the largest source of air pollution in Lithuania is the Oil Refinery in Mazeikiai. Pollution levels surrounding the refinery are the highest in Lithuania, reaching 2.4 Mg per km^2 for hydrocarbons and 1.6 Mg/km^2 for sulphur oxides in 1993.

In addition to local emissions, the transboundary transport of pollutants plays an important role in Lithuania. In 1990, 35 Gg of sulphur oxides was transported from Germany and 24 Gg from Poland (*Environmental...,* 1994). According to the estimates of the Lithuanian Institute of Physics, in 1992-1993 imports of sulphur and nitrogen oxides from neighbouring countries exceeded local emissions. Recent studies show that Lithuania's largest inputs of air pollutants are from Poland, Germany, the Czech Republic, and Slovakia (*Perkauskas et al.,* 1994). Significant levels of transboundary transport of pollutants was also confirmed by *Tuovinen et al.* (1994).

3. Energy Scenarios and Greenhouse Gas Emissions in Lithuania

Studies by the Lithuanian Energy Institute suggest that growth in food processing and light industry and away from more energy intensive processes in Lithuania will lead to a decreased demand for fossil fuels. The production of machine tools, metal hardware, forestry and timber goods, and paper and cellulose are energy intensive processes. Even more energy intensive are the production processes for construction materials, chemicals, and oil refining.

At present, thermal power plants and road traffic in Lithuania produce more than two-thirds of total greenhouse gas emissions. Both sources of pollution are planned to become primary targets of pollution-reducing programs. Energy and transportation sectors both operate on fossil fuels. Emissions from these sectors can be significantly reduced by measures such as fuel purification, introducing rational fuel-consumption strategies and introducing new technologies controlling emissions.

A great variety of different economic projections and scenarios were recently developed in Lithuania. The Ignalina Nuclear Power Plant (NPP) plays an extremely significant role in all of them. In 1993, this plant produced about

87 percent of electricity in Lithuania. At the same time, the unreliability of RBMK-type reactors and the construction shortcomings of the first Ignalina NPP reactor are causes for great concern. Shutdown of this reactor by 2000 is currently being discussed, however, this would cause a severe electricity deficit in Lithuania. To meet future energy needs under this scenario, a new power plant must be constructed.

The significance of the nuclear power station is reflected in the following two scenarios of energy production: I. Both reactors of Ignalina NPP are active until 2010; and II. Ignalina NPP is closed, and electric energy is produced by thermal plants. *Table 3* presents the estimated national emission levels for both scenarios. In scenario I, where Ignalina NPP remains active, the quantities of combustion products (CO_2, SO_x, and NO_x) would be significantly lower. If coal is used as a fuel for thermal power plants, SO_x emissions, according to scenario II, grow 2.4 times faster than in scenario I (*Zukauskas et al.*, 1994). Obviously, this is not a satisfactory solution and other strategies to meet energy needs must be developed.

Table 3. Combustion-related emissions in Lithuania by 2010 according to alternative energy-production scenarios

Scenario	CO_2 (Tg)	SO_x (Gg)	NO_x (Gg)
I	28	101	98
II	40	241	154

References

Burneikis, J., 1993: Air pollution in the main cities of Lithuania. *Energetika* 1, 16–19.

Environmental Protection Ministry of Lithuania, 1994: *Lietuvos gamtinė aplinka. Bûklė, procesai, tendencijos. Aplinkos apsaugos ministerija,* Vilnius.

Perkauskas, D., Senuta, K., and *Mikelinskienė, A.*, 1994: Model of long-range pollutants transport and acidity of precipitation for the Baltic Region. *Ecological Sustainability of Lithuania (ECOSLIT). 1993 Annual Report (abstract) II.* Lithuanian Academy of Sciences and International Center for Scientific Culture, World Laboratory Lithuanian Branch. 10.

Tuovinen, J.-P., Barret, K., and *Styve, H.*, 1994: *Transboundary Acidifying Pollution in Europe: Calculated Fields and Budgets* 1985-1993. EMEP/MSC-W Report 1/94.

Zukauskas, A., Jaskelevièius, B., Stumbras, A., and *Ziugzda, J.*, 1994: Determination of the combustion products released. *Ecological Sustainability of Lithuania (ECOSLIT). 1993 Annual Report (abstract) II.* Lithuanian Academy of Sciences and International Centre for Scientific Culture, World Laboratory Lithuanian Branch. 23–24.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

CO_2 Sinks and Emissions in Forests of the Russian Federation

A. O. Kokorin, A. L. Lelyakin, and **I. M. Nazarov**

Institute of Global Climate and Ecology,
Glebovskaya 20b 107258, Moscow, Russia

Abstract—A preliminary inventory of CO_2 sinks and emissions in different types of Russian forests was compiled. The level of inventory detail is significantly higher than in previous studies in Russia. The total forest area is practically constant in Russia, but now areas of middle-age forests are increasing. The detailed accounting of an internal carbon balance disturbance caused by past and current cutting, fires, and climate change was carried out for six regions with local warming trends. It was estimated that Russian forests store annually a net amount of 160 million metric tons of carbon. The significant sink — 51 million metric tons per year of carbon — is in South Siberia, where warming is the most important factor. The contribution of the European-Ural part of the country — 50 million metric tons per year of carbon — is also significant. However, the age distribution of the forests plays a key role in this region. Calculations show that it is very important to use primary data on regional warming and recent data on cutting during 1990–1993. It is necessary to improve data and calculations connected with forest fires and an influence of climate factors, especially, CO_2 fertilization.

Key-words: carbon dioxide, forests, sinks, inventory, climate changes, modelling.

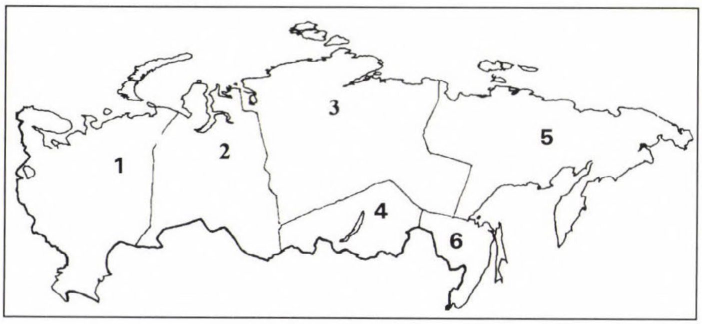
1. Introduction

According to recent studies, boreal and temperate forests are significant atmospheric CO_2 sinks. An important sink is the Russian taiga forests. Data on CO_2 sinks have been revised more than once during past few years. Methods of calculation have been improved and become more detailed as well (*Dixon et al.,* 1994; *Isaev et al.,* 1993; *Kokorin* and *Nazarov,* 1994, 1995; *Kolchugina* and *Vinson,* 1993).

A general approach to the estimating CO_2 sinks and emissions was summarized in the IPCC Guidelines *(IPCC,* 1994*)*. Using this approach as a starting point we applied CCBF (carbon and climate in boreal forest) dynamic model for calculations (*Kokorin* and *Nazarov,* 1994; *Kokorin* and *Lelyakin,* 1995). The model takes into account the majority of specific features of boreal and temperate forests, and underlying parameters, which were discussed by *Kokorin* and *Nazarov* (1995a). Here we present the main results of estimating CO_2 sinks and emissions and a short description of the model.

We based our work on data from the last Russian forest inventory, which was carried out by the Federal Forestry Service in 1993 (previous inventories were conducted in 1988, 1983, 1978, and earlier) (*Forest...*, 1990; *Handbook-...*, 1995). The forest inventory data were collected are using the existing breakdown of the Russian Federation by economic region and oblast (*Atlas...*, 1986; *Atlas...*, 1973). The data precision is adequate for the European-Ural part of the country, but it is significantly lower for large territories of Siberia and the Far East. Some areas were surveyed only once, 20 to 35 years ago (*Strakhov et al.*, 1995).

The forest zones and forest types distribution and climate regions distribution are very important for our purposes. Specific carbon content (in metric tons of carbon per hectare), as well as specific features of the carbon cycle in a forests are vary significantly across natural zones, described in *Atlas*... (1986) and *Atlas*... (1973). The climate regional breakdown, which was used before by the experts of the World Meteorological Organization (*Gruza et al.*, 1993), is presented in *Fig. 1*.



#	Region	Warming Increase in summer temperature in 1891-1992 years (*Gruza et.al., , 1993*) °C/100 yrs.
1	Europe-Ural	0.38
2	West Siberia	0.63
3	Central Siberia	0.39
4	South Siberia	1.49
5	North-East Siberia	0.81
6	Primorie and Priamurie	0.17

Fig. 1. Climate regions and warming trends on the territory of the Russian Federation.

2. *Forest Inventory Results*

Total area covered by forests in Russia is 763 Mha, including 705.8 Mha of forests managed by the Federal Forestry Service and about 57 Mha managed by other organizations. The forest inventory data were grouped into 30 ecoregions (*Table 1*) and flux calculations were carried out for every ecoregion separately.

Table 1. Areas of forests from the 1993 forest inventory (million ha)

Natural zone	Climate region						Total
	Europe-Ural	West Siberia	Central Siberia	South Siberia	N.-E. Siberia	Primorie and Priamurie	
Forest-tundra	8.6	8	56	–	54	–	126.6
North Taiga	26.7	21	12	–	8	–	67.7
Middle Taiga	56.1	23	155.5	65	12	–	311.6
South Taiga	29.9	28	–	49	–	54	160.9
Mixed North	12.5	2.8	–	–	–	12.4	27.7
Mixed South	9.3	0.9	–	–	–	7.4	17.6
Deciduous	12.8	4.6	–	2.2	–	8.2	27.8
Forest-steppe	10.1	3.7	–	9.8	–	–	23.6
Total	**166**	**92**	**223.5**	**126**	**74**	**82**	**763.5**

Table 2. Age distribution of Russian forests according to the last forest inventory in the year 1993 (*Handbook on Forest Fund of Russia*, 1995)

	Age distribution in percents				
	Young	Middle-age	Premature	Mature	Overmature
European-Ural part					
Forest inventory data	25.8	24.4	9.3	20.5	18.8
Estimation of the equilibrium age distribution	16.7	16.2	11.6	18.6	36.8
Asian part					
Forest inventory data	15.5	26.6	9.9	27.4	20.5
Estimation of the equilibrium age distribution	18.0	17.3	9.6	17.4	37.7

The age distribution of a forest is key to calculating possible carbon balance disturbances (*Table 2*). It is necessary to mention that about 50 percent of Russian forests are mixtures of trees of different ages, and the age distribution is far from equilibrium. Simulations with the CCBF model were based on two assumptions: age distribution in forests is close to equilibrium and in the absence of cutting and with the annual frequency of 0.003 intensive fires per year for overmature forests and 0.001 per year, for other forests 'preindustrial' carbon balance was in the state of 'quasi-equilibrium' (*Kokorin* and *Lelykin*, 1995; *Kokorin* and *Nazarov*, 1995).

The area and volume of forest cutting in Russia decreased rapidly from 1990 to 1993. Summary data on European and Asian regions are presented in *Table 3*. In the last years a smaller portion of post-cutting residues remained in the field, and a smaller volume of wood was removed from the forest. As a result, there was an additional increase of carbon storage in forests or an additional CO_2 sink. According to our calculations, the decrease in cutting after 1990 caused a significant additional CO_2 sequestration, estimated as 20 Tg C/yr.

Table 3. Area and volume of forest cuttings in the Russian Federation

Years	1970	1980	1985	1990	1991	1992	1993
			Area, 10^3 ha yr^{-1}				
European part	1340	979	938	829	712	627	485
Asian part	1001	762	745	793	705	606	436
			Volume, Mm^3 yr^{-1}				
European part	230	207	258	185	164	150	120
Asian part	125	142	142	145	131	115	83

We tried to compare the forest area data obtained in the last and the previous inventories. However, this comparison is difficult in Russia (*Strakhov et al.*, 1995). According to recently published forest inventory data (*Forest...*, 1990; *Handbook...*, 1995), the total change in forest area is about 1 percent, or 8 million hectares from 1988 to 1992, and practically all the change occurred in the poorly described lands of the Far East and Eastern Siberia, which are managed by the Federal Forestry Service (FFS) (*Table 4*). Such decrease cannot be explained by cutting or fires. It is reasonable to assume that this decrease results from an increased precision of measurements (*Dixon et al.*, 1994). In this report, we use the minimum estimate (no real forest area changes).

Table 4. Possible changes in the areas of the different age group forests (comparison of the last and the previous forest inventory data, 1988 and 1993 years) (million hectares)

Forests	Young	Middle-age	Premature	Mature	Overmature	**Total**
Change in area, Mha	4.4	20.8	-2.3	-28.4	-2.2	**-7.7**

The summary data on the total carbon stock in the Russian forests are collected in the *Table 5*. The basic data on specific carbon (C) contents (MgC/ha) and data on dependence of growth (Net Primary Production) on age of the forest were presented in the previous papers (*Kokorin* and *Nazarov*, 1994, 1995).

Table 5. Total carbon content in forest ecosystems of Russia, PgC

	Phyto-mass	Mort-mass	Total non-soil carbon	Labile humus	Total carbon without stable humus	Stable humus
	1	2	3=1+2	4	5=3+4	6
Forest-tundra	2.3	3.0	5.3	5.9	11.2	11.8
North Taiga	2.0	1.6	3.6	4.6	8.2	9.6
Middle Taiga	12.1	7.2	19.3	28.8	48.1	57.6
South Taiga	7.5	2.7	10.2	14.6	24.8	29.2
Mixed North	1.36	0.16	1.52	1.97	3.49	4.00
Mixed South	1.21	0.16	1.37	1.30	2.88	2.60
Deciduous	2.11	0.17	2.28	1.95	4.23	3.90
Forst-steppe, steppe	2.16	0.21	2.35	2.17	4.52	4.30
Total, forests managed by FFS	**30.7**	**15.2**	**46**	**61**	**107**	**123**
Forests managed by other organizations	**2.5**	**1.3**	**3.8**	**5**	**8.8**	**10**
Russian forests as a whole	**33.2**	**16.5**	**50**	**66**	**116**	**133**

The living biomass of Russian forests is about 33 Pg (10^{15} g) of carbon. This value is in good agreement with recent estimates reported by *Isaev* and co-authors (1993) and comparable values obtained for Canadian forests (*Simpson et al.,* 1993). However, some authors present different values. According to *Shvidenko* and *Kobak* (personal communications, 1995), the total biomass is equal to 20–25 Pg of carbon, and according to *Kolchugina* and *Vinson* (1993), it exceeds 33 PgC. It is very important to notice that almost all differences are connected with coefficients that are used for calculating specific carbon contents (Mg per hectare of carbon) (*Kokorin* and *Nazarov,* 1995). The general structure of the carbon budget is practically the same. It means that it is easy to correct CO_2 flux calculations if revised carbon data become available.

Mortmass carbon comprises about one half of phytomass carbon. Perhaps we overestimated mortmass because we had no information about the relationship between mortmass and forest age. In all cases we used values typical for mature forests.

The total carbon storage in all forest reservoirs can be estimated as 200 to 300 Pg of carbon. The greatest uncertainty is connected with stable humus, which contains one half of the total carbon but about which we have minimal data (*Kobak,* 1988). On the other hand, stable humus has a very long lifetime, and the possible influence of warming cannot cause a significant immediate CO_2 flux. Consequently, this uncertainty does not cause a significant difficulty when calculating CO_2 fluxes. Carbon storage without stable humus forms is equal to about 100 to 130 Pg of carbon. The labile humus contains from 55 to 75 Pg carbon. Living and dead organic matter amount to 33 and 17 Pg. The precision is 20 percent for labile humus forms and 10–15 percent for organic matter.

The total carbon storage in phytomass and mortmass is 50 PgC. Most of it (about 40 percent) is associated with the Middle Taiga zone. About one quarter is in the South Taiga zone.

3. Calculation of CO_2 Fluxes

The calculations of CO_2 fluxes were carried out using the CCBF (Carbon and Climate in Boreal Forest) model, which was developed in the Moscow Institute of Global Climate and Ecology for investigating the vulnerability of Russian forests to climate changes and for estimating the effects of mitigation options (*Kokorin* and *Nazarov,* 1994; *Kokorin* and *Nazarov,* 1995; *Kokorin* and *Lelyakin,* 1995). The model was used to calculate current fluxes (CO_2 inventory) on the basis of forest inventory data and data on changes in carbon content (land-use, fire, cutting, and so forth.).

The last version of the CCBF model was described recently in the U.S. Country Studies Training Workshops on Vulnerability (Honolulu, February 1995 and Warsaw, June 1995), as well as in the forest section of the 10th World Clean Air Congress (Helsinki, May 1995; *Kokorin et al.,* 1995). Thus, only a brief qualitative description of the model is presented here.

Characteristic features of our model are its orientation to certain types of forests as well as several details of a modeling approach. In general, our approach is based on carbon reservoirs, but it also has some features of 'gap' models. The model includes the following features:

- The accounting for all main reservoirs of carbon, including above- and below-ground biomass, litter, humus, dry stems (the last reservoir is a specific feature of large boreal forests), as well as consideration of possible climate effects;
- An explicit description of forest dynamics, with separate consideration of the development of separate age cohorts, processes of growth, competition, and tree death in a cohort;
- An explicit description of processes connected with forest fires and cutting.

The updated forest data obtained in 1993 were used. The processes of forest fires, cutting, and reforestation were calculated directly on the basis of primary data.

The 'unit area' of the model is a cohort of trees of the same age within a certain ecoregion (Table 1). Within the limit of an even-aged tree cohort, the processes of growth, competition and tree death are simulated. Cutting, forest fires, and climatic conditions are external factors. The interaction between trees of different cohorts is not taken into account.

The cohort areas are formed as a result of cutting, fires, and natural die-off in a cohort at the age T_{MAX}, and the remaining trees are placed into a special model reservoir, called 'Old trees in a young forest'. The growth of a new cohort begins in the next year after the cutting or die-off of an old cohort. Reforestation of burned out places occurs gradually. The rate of reforestation, as well as the 'limiting age' of burned-out places are parameters of a considered ecoregion.

Each cohort is a part of a reservoir of living above- and below-ground wood. The green biomass of trees, bushes, and grass cover are united in a common reservoir. Such simplification is possible at our timescale. A specific feature of Russian forests is the necessity to consider dry stems as a separate reservoir. The main parts of forests are not subject to careful cutting and the dry stems are not included in the statistics on cutting. They remain standing in a forest during several years in the temperate zone and from 20 to 40 and more years in the northern regions of a boreal zone (*Bazilevich,* 1993; *Shvidenko,* personal communication, 1995). Thus, the dry stems are significant stocks of carbon. Litter, which includes fallen trees, dead roots, and fallen branches, is the other component of forest mortmass.

Soil carbon is divided in two reservoirs that contain labile and stable forms of humus. This division is important just in boreal and temperate zones, where most of the carbon is in the soil humus. The humus consists of various forms with different decomposition and mineralization rates. Their ratio of carbon content in labile and stable forms of humus is about 1:2, and the ratio of their lifetimes is about 1:10 (*Kobak,* 1988).

In our model (as well as in ' gap' models), we use the universal qualitative dependence of a specific biomass on the age of a forest. The influence of climate factors on tree growth can be expressed by increasing growth rates. We used the simplest linear equations to describe this effect. The corresponding parameters were presented in previous papers (*Kokorin* and *Nazarov* 1994, 1995). The parameters reflecting climate impact on growth were based on parameters of the IMAGE 2.0 and ARP large-scale carbon-cycle models (*Moiseev et al.,* 1985; *Vloedbeld* and *Leemans,* 1993) and experimental data on the possible influence of warming on tree growth in boreal zones (*Kokorin* and *Nazarov,* 1995). The influence of two climate factors were considered in the calculations: the warming and prolongation of growth and decomposition periods; and the direct effect of atmospheric CO_2 on tree growth. Possible changes in precipitation were not taken into account. The possible reaction of the main types of Russian forest to changes in precipitation is assumed to be insignificant. Precipitation is a growth-limiting factor in the forest-steppe only. Moreover, current changes in precipitation are also quite small (*Gruza et al.,* 1993).

At present, climate changes result in a relatively small changes of average growth rate, which is considerably lower than interannual variations. At our time scale such an increase cannot exhaust soil reserves in boreal and temperate forests, where humus stocks are especially large. Because of that, changes in soil nutrition were not considered in the calculations.

Initial values of variables were based on assumptions about the preindustrial carbon equilibrium (*Kokorin* and *Nazarov,* 1995). We considered only the lands covered by forests and burned-out places in 1993. The model described the dynamics of carbon on these lands from 1870 to 1993.

4. *Results and Discussion*

We present here the summary results for all six climate regions and also the results, which illustrate the influence of the different factors: non-equilibrium age distribution, warming, and CO_2 concentration in the atmosphere. In Russia, forests are a net CO_2 sink, which is estimated as 160 Tg C/yr in 1993. All climate regions are sinks, but this effect is not uniform (*Fig. 2*). The South Siberian and European-Ural parts of Russia account for the largest portion of sequestered carbon, with nearly identical contributions of 51 and 50 Tg C/yr, respectively. The Central Siberian and Northeast Siberian regions contribute one half as much.

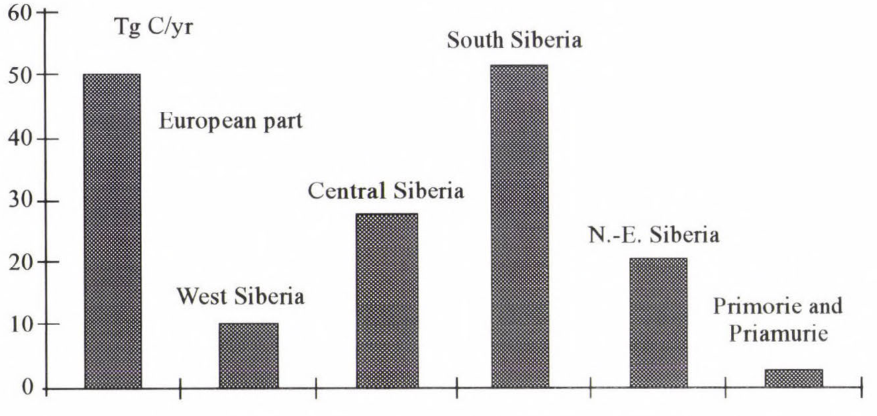


Fig. 2. Contributions of the different regions to a net carbon sink in Russian forests (total sink = 160 TgC/yr).

Specific CO_2 sinks (Mg C/(ha yr)) are presented in *Fig. 3*. The leading role of South Siberia is clear: the specific sink in this region is two times greater than the average value. On the other hand, the CO_2 uptake is not significant on large territories of West and Central Siberia, or in the Primorie and Priamurie regions (about 55 percent of the total forested area in Russia).

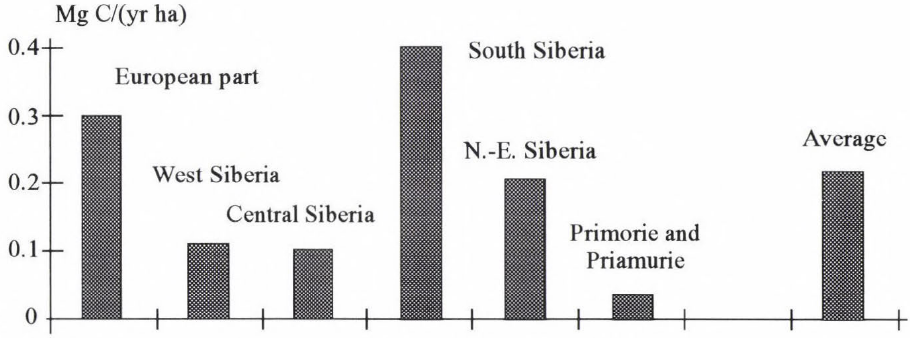


Fig. 3. Regional distribution of specific of CO_2 net sink in Russian forests.

Carbon sinks in forests were also estimated without accounting climate effects described in *Table 6*. This pure 'age distribution' effect in 1993 (there was a rapid decrease in cutting after 1990) is estimated as 72 Tg C/yr. The effect is significant, first of all, in the European-Ural region, where we can see the greatest excess of young and middle-aged forests. Other important timberlands, South Siberia, Priamurie, and Primorie, also make additional but small contributions. The remaining three regions, where cutting was not extensive, are characterized by insignificant sinks or emissions caused by age distribution.

It is interesting to notice that the pure 'age distribution' CO_2 sequestration is greater than the wood carbon removed from logged areas in 1993. According to our calculations, there is a sink amounting to 11 million metric tons per year of carbon even if all carbon removed is released in the atmosphere. The question about the relation between cut wood and emission is not clear in Russia. Part of this wood is fuelwood, part is used in products and long-living materials, and some of the timber is exported. The decomposition of old products and materials introduces an additional difficulty. In our current estimates (Figs. 2 and 3) we considered biomass removed from forests as a carbon loss or pure emission.

The influence of warming on tree growth and organic decomposition is supported by some models and experimental data (*Kokorin* and *Nazarov,* 1994, 1995; *Moiseev et al.,* 1985; *Kobak,* 1988). On the other hand, the warming trend is not always apparent. Another 'signal' — an increase in the atmospheric CO_2 — is quite clear, but its influence on boreal and temperate forests is not well known. In our estimates we used minimum values for corresponding parameters that were used in the large-scale carbon cycle models IMAGE 2.0 and ARP (*Moiseev et al.,* 1985; *Karaban et al.,* 1993; *Vloedbeld* and *Leemans,* 1993).

Table 6. The influence of the environmental factors on CO_2 sinks/emissions (Tg C/yr)

Effects	Climate regions						Total
	Europe-Ural	W. Siberia	Cent. Siberia	S. Siberia	N.-E. Siberia	Primorie Priamurie	
Absence of any climate effects (age distribution effect only)							
Sink caused by non-equilibrium age distribution only	55	-0.7	0.2	7.7	9.5	9.0	71.7
The same sink minus carbon of wood removed from cuttings in the year of inventory	21	-5.5	-2.0	1.0	0.2	-4.0	10.7
Absence of direct CO_2 influence on a tree growth (warming + age distribution effect)							
Regional interdecade trends of summer temperature: 1890-1930, 1930-1960, 1960-1990 and after 1990 (*Gruza et al.,* 1993)	34.0	3.7	12.6	39.1	15.9	-3.7	101.6
Average trend of annual temperature in Russia in 1891-1992, 0.55°C/100 yr	43.9	3.4	28.8	11.8	9.4	1.1	98.4

In the absence of CO_2 effect, the total sink (warming plus age distribution effect) is about 100 million metric tons of carbon per year (Table 6). The relative contributions of northern regions — Central and Northeast Siberia — are greater than with CO_2 fertilization effect, while the role of European areas becomes less important. The Primorie and Priamurie regions are characterized by little CO_2 emission.

It is important to notice that to model growth we used regional interdecade trends of summer temperature: 1890–1930, 1930–1960, 1960–1990, and after 1990 (*Gruza et al.,* 1993). The average increase of annual temperature in Russia from 1891 to 1992 was 0.55 degrees Celsius per 100 years. We sometimes used this value for general global estimates. The total effect is practically the same (Table 6).

It is interesting to compare the available estimates of the net total CO_2 sink and emissions in Russian forests. According to all authors, Russian forests are significant CO_2 sinks (*Dixon et al.,* 1994; *Isaev et al.,* 1993; *Kolchugina* and *Vinson,* 1994). A.S. Isaev and co-authors analyzed the age structure of forests and calculated that the total carbon sequestration caused by forest growth on forested areas (we considered here forested areas only) is about 184 million metric tons per year of carbon. It is difficult to compare this value with our estimates directly because we considered litter and soil decomposition processes and also possible climate effects. However, in general, both estimates are in good agreement.

According to the global review prepared by R.K. Dixon and co-authors, Russian forests are sequestering from 300 to 500 million metric tons per year of carbon (*Kolchugina* and *Vinson,* 1994), but Canadian forests (area is about 55 percent of the area of Russian forests) only about 80 million metric tons per year of carbon. The reasons for this difference are not clear now. Our estimate of the average specific net carbon sequestration, in Mg/(ha yr.), is close to the Canadian average estimates obtained by *M. J. Apps* and *W. A. Kurz* for 1991–1992. It is necessary to notice that the average accuracy of our estimates is about 20–30 percent.

5. Conclusions

Forests of the Russian Federation are a significant CO_2 net sink that was estimated as 160 million metric tons of carbon in 1993. Most carbon accumulation occur in the South Siberia and European-Ural regions of Russia. However, on average, specific CO_2 uptake (carbon sequestration per hectare) is modest, which is usual for non-tropical forests with a low level of management. The accuracy of the estimates is about 20 to 30 percent (up to 50 percent in Central and Northeast Siberia).

The influence of large areas of young and middle-aged forests is significant, especially in the European-Ural region. It is important to take into account the decrease of cutting in Russia in the last decade.

On the other hand, change in the total forest area caused by changes in land-use during the last 5 years did not significantly affect CO_2 sinks and emissions in the Russian Federation.

The influence of current warming plays a key role in CO_2 uptake, especially in South Siberia. It is important to use regional climate data for CO_2 sinks and emissions estimates.

The results presented here are preliminary. Some data, such as data on the current forest areas, are final (as accurate as possible). On the other hand, estimates of emissions from forest fires and the influence of atmospheric CO_2 on tree growth are only first approximations.

Acknowledgment—This work was carried out under the U.S. Country Studies Program, Cooperative Agreement DE-FCO2-93PO10118, with the U.S. Department of Energy. The authors would like to express their gratitude to *Robert K. Dixon*, EPA, Director of the U.S. Country Studies Program, and *John Millhone*, Project Officer of the Program, for review and valuable comments.

References

Atlas of the USSR (in Russian), 1986. GUGK, Moscow.

Atlas of Forests of the USSR (in Russian). 1973. Goskomles, Moscow.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., and *J. Wisnievwski,* 1994: *Science 263,* 185-190.

Forest Fund of the USSR (in Russian). 1990. Goskomles, Moscow. Vol. 1 and 2.

Gruza, G.V., Rankova, E.Ya., and *Rocheva, E.V., 1993: Comparison of 1931-1960 and 1961-1990 Air Temperature Normals for the Territory of the Former USSR*, 276-280. 18th Annual Climate Diagnosis Workshops, Nov. 1-5, 1993. NOAA, Boulder, CO USA.

Handbook on Forest Fund of Russia (in Russian). 1995. Federal Forestry Service, Moscow.

IPCC/OECD, 1994: *Draft Guidelines for National GHG Inventories*. Vol. 2 and 3.

Isaev, A.S., Korovin, G.N., Utkin, A.I., Prjazhnikov, A.A., and *Zamolodchikov, D.G.*, 1993: The estimation of carbon content and annual deposition in phytomass of Russian forest ecosystems (in Russian). *Lesovedenie*, No. 5, 3–10.

Karaban, R.T., Kokorin, A.O., Nazarov, I.M., and *Shvidenko, A.Z.,* 1993: CO_2 sequestration by Russian Forests (in Russian). *Meteorol. and Hydrol. Rus. J.* No. 1, 5–14.

Kobak, K.I., 1988: *Biotic Components of the Carbon Cycle* (in Russian). Hydrometeoizdat. Leningrad.

Kokorin, A.O. and *Nazarov, I.M.,* 1994: Evaluation of the effect of climate warming and photosynthetically-active radiation on boreal forests (in Russian). *Meteorology and Hydrol. Rus. J.*, No. 5, 44-54.

Kokorin, A.O. and *Lelyakin, A.L.,* 1995: Model for calculation of CO_2 fluxes in forest-atmosphere system caused by non-equilibrium age structure and fires (in Russian). *Problems of ecological monitoring and ecosystem modeling. Vol. 16,* p.18 (in press).

Kokorin, A.O. and *Nazarov, I.M.,* 1995: The analysis of growth parameters of Russian boreal forests in warming, and its use in carbon budget model. *Ecological Modeling*, (in press) 12.

Kokorin, A.O. and *Nazarov, I.M.,* 1995a: Specific requirements to methodology for estimating of CO_2 fluxes in boreal and temperate forests. *Report on Eastern European Workshop on GHG Emission Inventories, Budapest, 8–11 May 1995,* p.8.

Kokorin, A.O., Lelakin, A.L., and *Nazarov, I.M.,* 1995: The influence of climate changes on the carbon cycle in the Russian forests. Data inventory and long-scale model prognoses. *Proceedings of 10^{th} World Clean Air Congress, Helsinki, 28 May–2 June, 1995,* vol.3, report 439, p.4.

Kolchugina, T.P., and *Vinson, T.S.,* 1993: Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. *Water, Air and Soil Pollut. 70,* 207–221.

Kolchugina, T.P. and *Vinson, T.S.,* 1994: Production of greenhouse gases in the former Soviet Union. *World Resource Review 6,* 291–303.

Moiseev, N.N., Alexandrov, V.V., and *Tarko, A.M.,* 1985: *Man and Biosphere. An Experience in System Analysis and Model Experiments* (in Russian). Nauka, Moscow.

Simpson, L.G., Botkin, D.B., and *Nisbert, R.A.,* 1993: The potential aboveground carbon storage of North American forests. *Water, Air and Soil Pollut. 70,* 197–206.

Strakhov, V.V., Filipchuk, A.N., and *Shvidenko, A.Z.,* 1995: On changes in forest registration in Russia (in Russian). *Forestry.* No. 1, 11–14.

Vloedbeld, M. and *Leemans, R.,* 1993: Quantifying feedback processes in the response of the terrestrial carbon cycle to global change: The modeling approach of IMAGE 2.0. *Water, Air and Soil Pollut. 70,* 615–628.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Preliminary Results of CH_4 and N_2O Emission Estimation in Slovakia

Katarína Marečková

Slovak Hydrometeorological Institute,
Jeséniova 17, SK–835 15 Bratislava, Slovakia

Abstract—Estimates of quantities of emissions are calculated by applying the *IPCC Draft Guidelines for National Greenhouse Gas Inventories* (*IPCC,* 1994). The main source category of GHGs in Slovakia is combustion of fossil fuels. While the combustion of fossil fuels accounts for about 96 percent of total Slovakian CO_2 emissions, CO_2 also results directly from industrial processes. The most relevant industrial activities in Slovakia concerning carbon dioxide in 1990 were cement and magnesite production, processes in the iron and steel industry, petroleum processing, coke production, glass and ceramics production, and aluminia production. In 1990, as a result of biological processes and anthropogenic activities in forests, CO_2 was removed from the atmosphere. The total CO_2 emissions in 1990 were 58, 278 Gg.

The main sources of methane emissions are livestock farming, local networks of natural gas distribution, and landfills, with total estimated emissions of 347 Gg CH_4.

Compared to the other GHGs, the emissions of N_2O are not fully understood. The main sources are expected to be agriculture and waste-water treatment. The estimated emission of 16 Gg is preliminary.

To evaluate the share of different GHGs in total emissions, the aggregated emissions were estimated, based on both the direct and indirect effects. In Slovakia, CO_2 emissions amount to 81 percent of total emissions, CH_4 emissions amount to 11 percent and N_2O emissions amount to 8 percent.

1. Introduction

Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, their recent atmospheric build-up appears to be largely the result of human activities. This build-up has altered the composition of the Earth's atmosphere and may affect global climate.

This paper presents the preliminary results of the greenhouse gas emissions inventory in Slovakia for the base year 1990, focusing on methane and nitrogen dioxide. The final version is expected in early 1996 and will be elaborated within the National Country Study to address climate change and with support of the Slovakian Ministry of Environment. The work is coordinated by the

Slovak Hydrometeorological Institute. The results of the inventory are included in the First National Communication.

The key gases included in the inventory are CO_2, CH_4, and N_2O. Chlorofluorocarbons are excluded, because they are controlled by the Montreal Protocol.

Estimates of quantities of emissions are calculated according to the *IPCC Draft Guidelines for National Greenhouse Gas Inventories, IPCC* (1994), taking into account national circumstances. All emissions are expressed in full molecular mass (for example, Gg CO_2).

2. *CH_4 Emissions*

Fig. 1 gives CH_4 emissions according to individual sectors. The major sources of methane in Slovakia are waste handling, agriculture, and fuel extraction and transportation, [CH_4 emissions are specified by the IPCC methodology (bottom-up)], with livestock farming in agriculture being the major anthropogenic source of methane emissions. CH_4 is formed as a direct product of the metabolism of herbivorous animals and as the product of organic degradation of animal waste. Calculations of emissions for the Slovak Republic come are based on the concept and principles of agricultural policy from 1993; the emission factors were modified according to specific national conditions. Between 1990 and 1993, the number of cattle decreased considerably as a result of the transformation from a planned economy to the market system, and thus CH_4 emissions decreased considerably as well. Agricultural concepts assume that in 2000, the number of cattle will be approximately the same as in 1990 (*Kučírek,* 1995). Emissions resulting from communal waste landfilling (open dumps) were specified in a separate study, based on specific communal waste production per inhabitant and on the estimated volume of degradable organic carbon in the waste (*Vančová,* 1994). IPCC methodology was used, applying a local factor of 0.5. Emissions from sewage water and sludge handling are not included.

Figure 1 Sectorial share

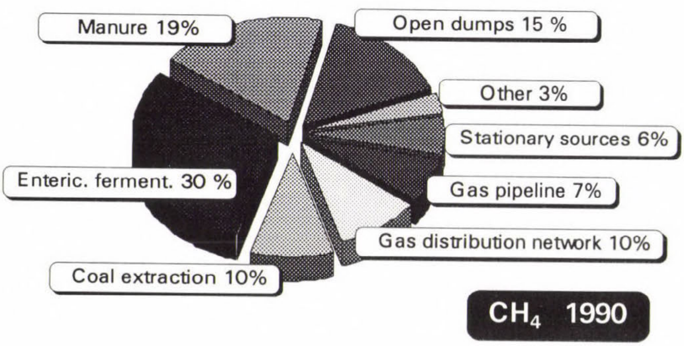


Table 1. CH_4 emissions (Gg) in 1990 and 1993

	1990	1993
Fossil fuel combustion	21	
Stationary sources	20	
Transport	1	1
Fugitive emissions	96	
Gas extraction	4	
Gas pipeline	24	
Gas distribution network	35	165[1]
Brown coal/lignite extraction	3	
Agriculture	172	112
Enteric fermentation	106	68
Manure	65	43
Waste incineration	1	1[2]
Waste treatment		
Open dumps	53	58
Forest ecosystems	5	(5)
Total	347	

[1] year 1992 [2] expert estimation

In Slovakia, fossil fuel extraction and transportation represent an important source of methane (*Table 1*). The volume of methane liberated during brown coal and lignite extraction was specified by applying the emission factor of 7 kg CH_4/Mg of extracted coal. These values might be too high. The amount of natural gas transmitted via pipeline is about ten times greater than the amount used in the country. Methane emissions from losses during natural gas distribution are specified very roughly, according to statistically recorded natural gas losses in the distribution networks (*Marečková,* 1994). These values will have to be specified more precisely.

Methane emissions from fossil fuel incineration were specified on the basis of the consumed fuel registered in the national inventory system REZZO, by applying the balance method. Emission factors were according to *Veldt* (1991).

3. N_2O Emissions

Compared to other greenhouse gases, the mechanism of nitrous oxide emissions and sinks has not been investigated completely. A complete list of N_2O sources and emissions could not be provided for the Slovak region.

Emissions in power engineering and transport were specified on the basis of the fossil fuel consumption balance, by applying emission factors from the literature.

In the agricultural sector, the nitrogen balance in arable land and in biomass was assessed, considering various types of soil and vegetation, as well as the application of mineral and organic fertilizers. N_2O emissions are caused by an excess of mineral nitrogen in soil as a consequence of intense fertilization and of an unfavorable air regime in soil (the use of heavy machinery during cultivation). The method of indirect evaluation of the intensity of these processes was used (*IPCC,* 1994). From the early 1990s, the average consumption of fertilizers decreased consequent to the economic recession. In 1990, approximately 138 kg N per ha, in 1993 approximately 60 kg of N per ha. It is

Table 2. N_2O emissions (Gg) in 1990 and 1993

	1990	1993
Energy	3.8	
Energy/heat generation	3.6	NE
Transport	0.2	0.2
Industry	2.1	1.1
Agriculture	8.8	3.6
Arable land	8.8	3.6
Waste incineration	0.02	0.02[1]
Forest ecosystems-Water surfaces	1.3	1.3
Total	16.0	

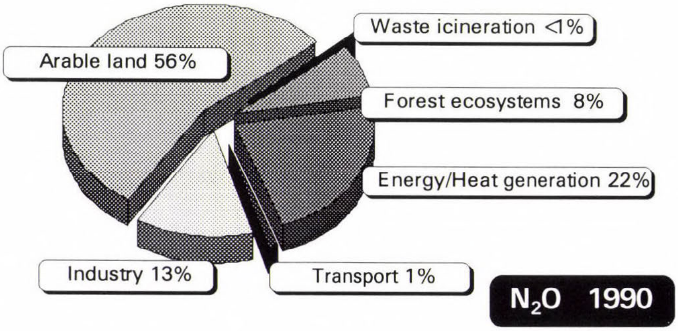
[1] expert estimation

assumed that in 2000 the fertilizer consumption will reach the level of 1990 again (*Bielek,* 1995).

Emissions from water surfaces were calculated by applying the emission factors given in literature (*CITEPA*, 1992) for 1990 and should not change decisively during the coming years.

Emissions occurring during waste handling are specified only roughly. Calculated emissions show a high inaccuracy which, however, is difficult to quantify—with certain emission factors, even 100 percent are possible (*Fig. 2*).

Figure 2 Sectorial share



4. Aggregated Emissions

Global Warming Potential

	GWP 20 years	GWP 100 years
Carbon dioxide	1	1
Nitrous oxide	290	320
Methane	62	24.5
IPCC Report 1994		

This section gives the emissions in aggregated form for comparing the contributions of individual greenhouse gases to the overall greenhouse effect. The emissions of individual greenhouse gases are based on the global warming potential (GWP) for the time horizon of 100 years. Typical uncertainty is $\pm$ 35 percent.

The values of aggregated emissions consider both primary and secondary contributions of greenhouse gases according to the IPCC methodology (*Table 3*). CO_2 emissions contribute 81 percent to total emissions (expressed as the CO_2 equivalent), CH_4 emissions contribute 11 percent, and N_2O emissions 8 percent (cf. *Fig. 3*).

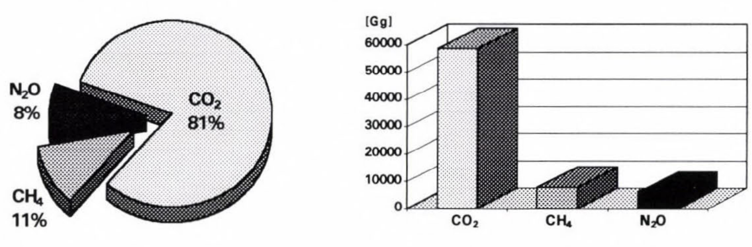
Table 3. Aggregated emissions considering direct and indirect effects of CO_2, CH_4 and N_2O emitted in 1990

	CO_2 (Gg)	CH_4 (Gg CO_2 equivalent)	N_2O	Aggregated
Energy/heat generation	5 5 033	521	1 212	56 766
Fugitive emissions	0	1 767	0	1 767
Industry	2 775	0	658	3 433
Agriculture	0	4 190	4 435	8 625
Forestry	(-4 451)[1]	120 [2]	410	530
Waste treatment	470	1 294	38	1 802
Total	58 278	7 892	6 753	72 923

[1] carbon sinks are not included in total CO_2 emission [2] emissions from wetlands

Figure 3 Aggregated GHGs emissions

expressed in % expressed in Gg CO_2



5. Conclusion

The Slovak Republic's share of global anthropogenic greenhouse gas emissions is approximately 0.2 percent. Annual per capita emissions (14 tons of CO_2 equivalent in 1990) is lower than the OECD countries average. Nevertheless, it places Slovakia among 15 states with the highest per capita emissions. The share of CH_4 and N_2O is as much as 20 percent.

The data on methane and nitrous oxide presented in this report cannot be considered as final. In Slovakia, first studies on these problems were started in 1993, identifying the GHGs emission sources and specifying first emission estimates. Because of limited financial resources, more accurate information on sources and emissions can be obtained only by gradual steps. At present, several projects are under way, financed by the Environmental Fund of the Slovak Republic, the budget of the Ministry of Environment and the US support within the Country Studies project. These projects' contributions are necessary to obtain more accurate information on sources, emissions, and sinks of greenhouse gases in Slovakia.

References

Bielek, P., 1995: *Nitrous Oxide Emissions from Agricultural Soils in the Slovak Republics. Draft Report.* Bratislava.

CITEPA, Default Emission Factors Handbook, 1992: under the contract of the CEC–DG XI.

IPCC, 1994: *Draft Guidelines for National Greenhouse Gas Inventories.* Vol. 3.

Kučírek, S., 1995: *Methane Emissions from Livestock, Farming. Draft Report.* Bratislava.

Marečková, K., 1994: *CORINAIR 90 Emissions Inventory for Slovakia, Final Report.* SHMU, Bratislava.

Vančová, A., 1995: *Emisie skleníkových plynov v odpadovm hospodárstve.* SHMU, Bratislava.

Veldt, C., 1991: *Development of EMEP and CORINAIR Emission Factors and Species Profiles for Emissions of Organic Compounds.* TNO. Draft Report. The Netherlands.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Long Term Trends in Meteorological Variables, Pollutant Emissions and Concentrations in Latvia

G. Matisone[1], **M. Treiliba**[1], **I. Apene**[2], and **V. Bergmanis**[2]

[1] *Latvian State Hydrometeorological Agency, 165 Maskavas str., LV-1019, Riga, Latvia*
[2] *Ministry of the Environmental Protection and Regional Development of the Republic of Latvia, 25, Peldu str., LV-1494, Riga, Latvia*

Abstract—This paper examines a broader approach to the Greenhouse Gas (GHG) Inventory and includes two important aspects, meteorological and contamination of the atmosphere with GHG and related gases. In Latvia, meteorological observation data are available at 24 meteorological stations for a period of up to 100 years and more. CO_2, CH_4, N_2O, NO_x and NMVOC emissions have been measured according to the IPCC Draft Guidelines for National GHG Emission Inventories. Regular inventories of air pollution from stationary sources have been made since 1980. Long-term observations and emissions data from local sources indirectly testify to the pollution level formation in the atmosphere due to local sources rather than to regional ones.

Key-words: greenhouse gases, meteorological observations, environmental pollution observations.

1. General Information about Latvia

Latvia is situated on the edge of the Eastern European plain, on the coast of the Baltic Sea. The location and the proximity of the Atlantic Ocean determines climatic conditions, moderately warm summers, moderately cold winters, frequent cyclones. Of the total land area of Latvia, cultivated lands constitute 39%, and forests, shrubs and groves constitute 44%. The population is about 2.7 million. The national contribution of Latvia to Gross World Product constitutes 0.04% as compared to 26.3% from the USA.

Latvian economy is in the transition period from centralized planning to the market economy, and is facing a crisis in all sectors of national activities, specifically in the energy sector and industry. The energy sector has no considerable resources of its own. Fifty percent of electricity and 90% of fuels have been imported. In terms of energy resources, the transition to market prices affects Latvian economy exceptionally severely.

No particular national policy to mitigate climate change has been developed. Current policy is a combination of environmental protection policy and development strategies in the various economic sectors, and depends more on business recession than on any active steps to be taken to reduce emissions.

2. Trends in Meteorological Variables

Observations of weather phenomena have uses which go well beyond the immediate and seasonal forecasts determining day to day human activity. Long-range studies of the atmosphere are crucial in understanding climate change or global warming. Many scientists have warned that CO_2 and other GHG emissions in the atmosphere will raise the earth's temperature with devastating consequences for human beings, animal and plant life over the coming decades and centuries.

Observation data on air temperature, relative humidity, cloudiness, atmospheric precipitation and sunshine duration available at 24 meteorological stations of Latvia were processed with an effort to determine trends in the main meteorological elements over the last 50 years of extensive human activities (*Zirnitis*, 1983).

To establish trends in the meteorological variables, the data set analysis was simplified with an assumption that variations were close to linear over the whole period. A method of least squares was used to define coefficient of the regression line.

Air temperature observations have shown increasing warming over the territory of Latvia. Comparisons made of the values for the recent 100-year period testify to a more rapid rise in temperature for the second half of the period. During the first 50 years, annual mean air temperature rise averaged 0.2°C without an obvious effect from the populated areas and the level of economic development. In the second half of the period, impact on Riga, the largest city and industrial center, was evident. The mean annual temperature in Riga was 1°C higher in contrast to 0.5°C for the rest of the country (*Fig. 1*).

The air temperature amplitude has become narrower. The greatest positive changes occur in the winter months, mainly due to the temperature increase at night. Mean annual extreme values have moved closer, and the mean minimum is increasing faster than the maximum mean.

Annual precipitation has become more abundant. The process was more obvious in districts where prevailing winds and the relief fostered the ascent of air masses. During the year, the increase was more evident early in the cold period (*Fig. 2*).

Total cloud quantity has remained unchanged with some reduction in the low cloud quantity. Despite this fact, the analysis shows that sunshine duration has become shorter and the mean annual relative humidity remains unchanged.

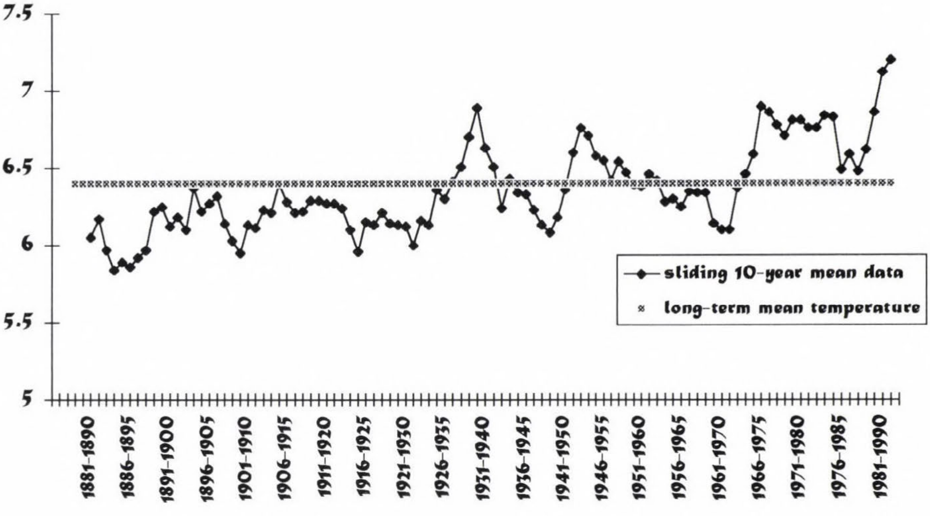


Fig. 1. Mean annual air temperature in Riga, Latvia.

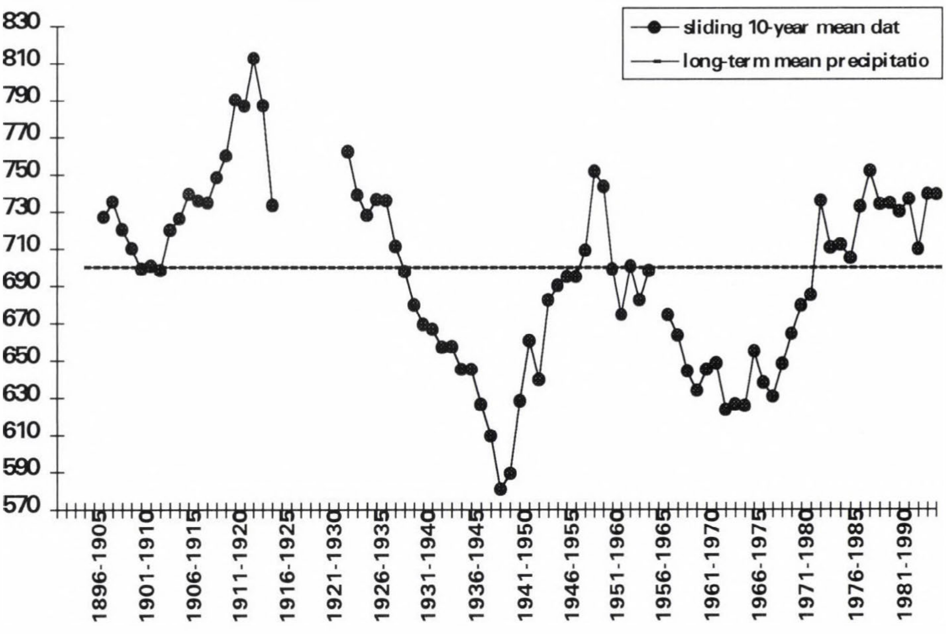


Fig. 2. Annual precipitation amount in Liepaja, Latvia.

3. Meteorological Observations in Latvia

The first information about weather observations (thunderstorms) in Latvia dates back to the years 1680–1690. A hundred years later, air temperature and wind measurements were made several times a day at a station in Riga. Since 1795, the station has provided for other meteorological observations including atmospheric pressure.

In the nineteenth century, 16 meteorological stations and 29 posts covered Kurzeme, Zemgale, Vidzeme and Latgale historical districts (*Climate...*, 1968). The first of these were established in Jelgava (1812), Kuldiga (1829), Valmiera (1835), Kabile (1843), Bauska (1850), Puze and Lubana (1853), Liepaja (1857).

The work of the stations was discontinued during World Wars I and II. Establishment of the basic observational network started in the 1920s and was completed in the 1940s.

Nowadays Latvian meteorologists strictly adhere to the guidelines and recommendations of the World Meteorological Organization. The hydrometeorological observation complex includes (*Fig. 3*):

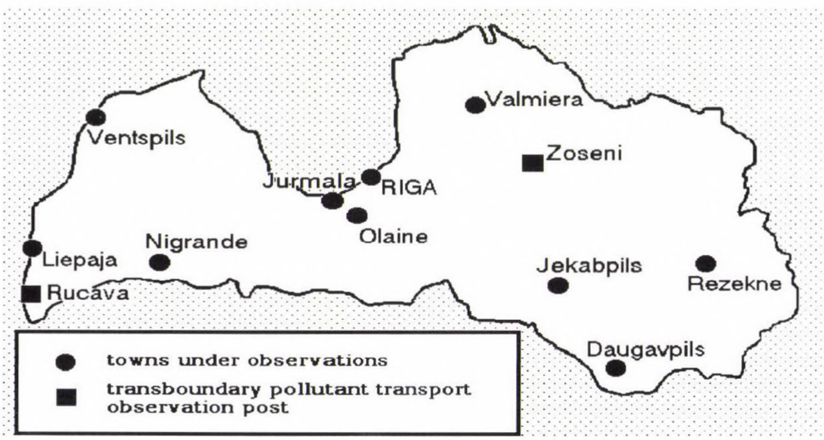


Fig.3. Network of meteorological and specialized observations posts in Latvia.

- full-program meteorological observations performed at 24 stations. The density of the network is 1 station per 2.650 km^2. The duration of the observations made at 19 stations is about 40 years and at 5 stations is more than 70 years. Nine stations are included in the Global Telecommunication System (GTS) for international information exchange;
- precipitation observations performed at 86 hydrometeorological posts. The density of the network is 1 post per 740 km^2;
- aerological observations at 1 station;

- radar meteorological observations at 2 stations (in Riga and Liepaja);
- hydrological observations at 64 riverine posts, 53 of which also measure the volume of the water discharge, at 8 posts in lakes and 4 posts on water reservoirs;
- marine hydrometeorological observations at 10 stations in the littoral zone of the Baltic Sea and the Gulf of Riga;
- full-program agrometeorological observations at 11 stations;
- abridged program at 13 posts;
- specialized hydrometeorological observations at 2 aeronautical meteorological stations, 1 water balance stations, 1 agrometeorological station, 1 bog post, 1 river mouth station and 1 bioclimatological station;
- specialized geophysical observations: actinometric and heat balance observations at 1 station, total daily solar radiation at 3 stations and ground-based ozone observations at 1 station; and
- 38 ship-based marine hydrometeorological observations.

4. A Decade of Weather Anomalies in Latvia (1984–1994)

From 1984–1994, repeated weather anomalies occurred in Latvia (*Summary...*, 1995). Major destructions were brought by frequent storms on the sea coast, especially in autumn and winter. In February 1990, wind speeds of up to 20–27 m/s occurred over a period of 20 days. An extremely strong storm was recorded in the middle of January 1993. Wind gusts of 30–32 m/s were recorded on the coast and in most of the southern regions, 35 m/s in the town of Jekabpils and 38 m/s in Liepaja. The return time of such winds is 20 years (50 years in Liepaja and Jekabpils). Western winds caused an enormous water inflow to the Gulf of Riga and the Western Daugava river from the Baltic. Water level was on a mark of 160 cm near Riga, and low-lying land around the city was flooded. In July 1988, during a severe gale (28–30 m/s) in the Gulf of Riga, the wind and waves threw boats onto the shore and some seamen died.

Thunderstorms and whirlwinds have occurred in summer, with gusts of 28–30 m/s and greater. During a thunderstorm in western Latvia in June 1985, fish ponds were emptied, roofs torn off and a tractor was lifted off the ground.

In June 1991, a whirlwind enveloped the south-eastern region of Daugavpils, blowing down trees and wires; trams did not run for some 24 hours. Probable recurrence of the phenomenon is one to three times in 10 years.

Winter thunderstorms in the coastal zone have occurred once every five to ten years. In January 1993, thunderstorms were recorded by five hydrometeorological stations far inland, in the eastern regions of the country. It is worth mentioning that over the previous 100 years winter thunderstorms were not recorded in these areas.

5. Other Abnormal Meteorological Phenomena

5.1 Snowstorms

Between 22 and 24 April 1988, a 20-hour snowstorm occurred in Riga. In other regions, roads and agricultural lands were covered with snow. Migratory birds from warm lands had no food and many of them died. The return time of such weather conditions observed so late in April is once in 20 years.

5.2 Drought

Warm and dry weather prevailed in May and June 1992. In the middle of May, warm and dry weather was settled and lasted till June. At the end of June, soil moisture deficit was observed at a depth of 0.5 m and of one meter in some parts. Plants and tree roots were damaged. Groundwater level decreased by 50 to 80 cm, grass became yellowed and burned. Some crops were totally lost, and fires destroyed extensive wooded areas. During the growing season, only half of the normal amount of rain fell. In July and August, abnormally high temperatures of 30–32°C were recorded, with absolute maximum values of 35°C and 36°C in August. The summer of 1992 lasted for 40 days, and was longer than normal. Such hot, arid summers have been recorded only three times during the present century.

Starting from June 26, 1994, when a period of summer rainfall starts, very warm, dry and sunny weather set in. Late in July, maximum air temperature increased up to 32–35°C, reaching an absolute maximum of 36°C in the Southern part of Latvia. During that time, there were only three days of precipitation instead of the 15–16 day norm. In the southern part of the country, not a single raindrop fell. Because of hot and dry weather conditions, fires started very often, causing much damage to woods. In total, 719 fires occurred within a 310 hectare territory.

5.3 Abnormally Warm Winters

From 1988 to 1993 several consecutive winters have been unusually warm. Early in January 1992, daytime temperatures in the north were the highest ever recorded for the month (10°C). In Kurzeme, in the district of Saldus, flowers bloomed, lilac buds started to open and fruit trees blossomed.

The month of February in 1989 and 1990 was unusually warm. Maximum temperatures of 15°C were recorded on the coast in Pavilosta and Liepaja. Late in February, in Kurzeme, sap rose in birches, snowdrops blossomed, winter crops started to grow again and, in the middle of the month, current buds started to open. In other words, spring began 1.5–2 months earlier than usual. In 1989, January was 6–7.6°C warmer than normal and February was 7–8°C warmer. In 1990, the corresponding value was 7.5–9.9°C.

Over the previous 100 years, such anomalies were not observed.

6. Environmental Pollution Observations

The density of the environment pollution observation network is approximately 1 station per 300 km^2. Key principles of the observations are comprehensiveness, identity and common methodology. The performance of environmental pollution observations including evaluation of transboundary pollution transport are conducted by the Environmental Pollution Observation Center (EPOC) of National Hydrometeorological Service. Founded 15 years ago, it is still a well-functioning operational unit.

6.1 Air Pollution Observations

Air pollution observations are being made at 21 posts in 11 towns including 2 posts for transboundary air pollution monitoring in Rucava and Zoseni, which participate (Rucava since 1985 and Zoseni since 1994) in the Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP). Routine observations are performed 3–4 times per day, and continuous daily observations are made at the EMEP stations (*Lyulko et al.*, 1993).

More than 20 harmful substances, including nitrogen and sulfur oxides, carbon oxides, ammonium, heavy metals, tropospheric ozone, benzopyrene, phenol, and others, are measured. Additionally, specific compounds are measured in some cities (*Short Review...*, 1990, 1991; *Environmental...*,1992, 1993, 1994, 1995).

6.2 Ozone Measurements

In Latvia, total ozone measurements started in August 1961. The Riga ozone station is included in the global and regional observational networks.

In 1994, surface ozone measurements started at Rucava. High mean daily values (61–90 $\mu g/m^3$) were on record in the spring-summer period. In autumn, the concentrations were within 31–60 $\mu g/m^3$. Most of the mean daily values exceeded the mean daily permitted concentration over the whole observational period. A maximum concentration of 151 $\mu g/m^3$ once observed was lower than the once maximum permitted concentration. The surface ozone measurements made in Riga by the Municipal Air Quality Management Office showed practically analogous mean daily maximum values. Mean daily surface ozone concentrations at Rucava were higher than the maximum permitted concentration. Maximum values were obtained during the spring-summer period. Values for Riga were practically analogous to mean daily maximum data.

7. *Inventory of Emissions*

7.1 *Trends in Emissions in 1980–1994*

Regular accounting of air pollution from stationary sources has been made since 1980, when an inventory of stationary pollutant-emitting sources started. This explains the highest emissions of 289.4 thousand tonnes of pollutants observed that year. From 1982, total emissions have been decreasing and amounted to 87.2 thousand tonnes in 1993 (*Fig. 4*). The decrease was gained mainly due to the installation of collectors for solid particles; introduction of technological equipment for nitrogen oxide reduction; shift towards different combustion fuels and loss in industrial output. A 19.1% increase was recorded in the total pollutant emissions in 1994. In 1994, pollutant emissions from stationary sources were mainly composed of sulfur dioxide and nitrogen oxide (59.6%), carbon monoxide (23.8%).

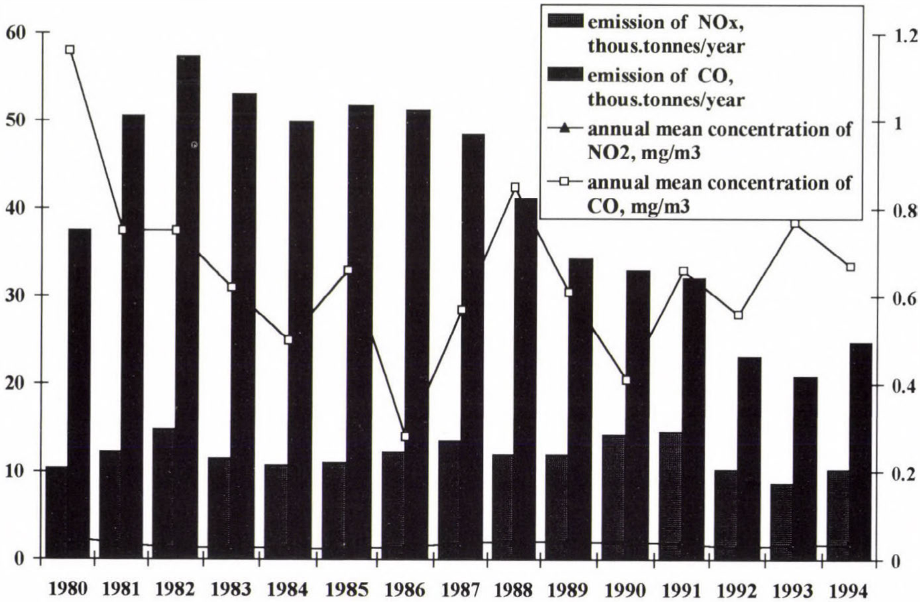


Fig.4. Emissions and annual concentrations of NO_x and CO in Latvia (emissions – left axis, concentrations – right axis).

One hundred and thirty-seven pollutants other than those mentioned above constituted only 16.6% of the total accounted substances.

An uneven pollutant emissions pattern resulted from the location of industrial enterprises in the largest and most densely populated towns. Over one half of emissions has been recorded in these towns. Riga stands out, contributing 30.7% to total emissions. Emissions from heating installations contribute much to the total pollutant emissions from stationary sources (84%).

In 1994, sulfur dioxide and nitrogen oxide emissions from stationary sources increased by 15.4% and 15.1%, respectively (*Fig. 5* and *6*). This is attributed to a shift towards different fossil fuels in 1994 and small boiling houses additionally registered in some districts. That year, more fuel oil was burned than natural gas because of a great difference in price.

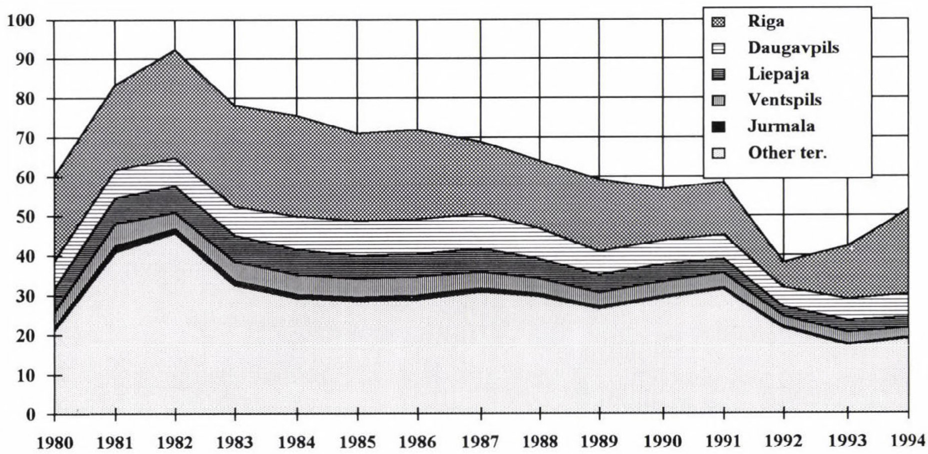


Fig.5. Dynamics of sulfur dioxide emissions in Latvia (thous.tonnes/year).

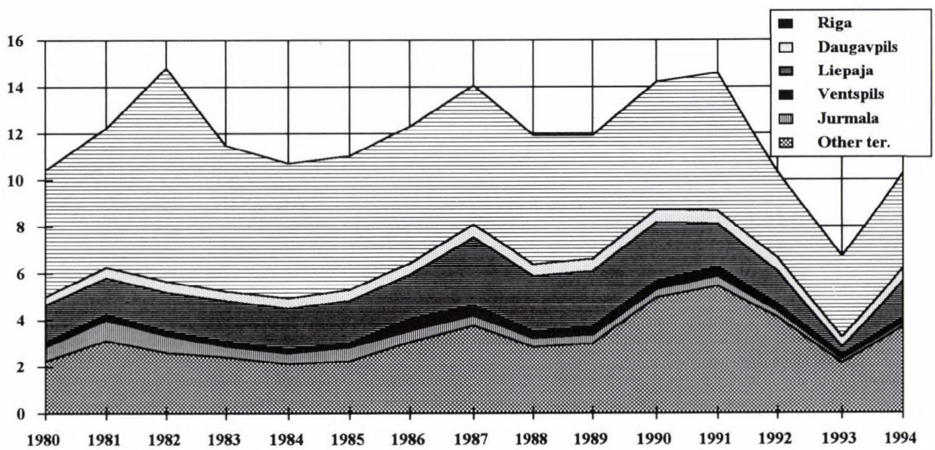


Fig.6. Dynamics of nitrogen oxides emissions in Latvia (thous.tonnes/year).

7.2 Greenhouse Gas Inventories

According to the IPCC Draft Guidelines for National GHG Inventories the following gases have been measured in Latvia: CO_2, CH_4, N_2O, NO_x, and NMVOC. In 1990, the total GHG emissions (thousand tones) were as follows: CO_2 — 22976.3, CH_4 — 158.937, N_2O — 2.38, NO_x — 90.135, CO — 363.125, and (NM)VOC — 62.722. Combustion of fossil fuels is the main source of CO_2, whereas agriculture produces most of CH_4. In 1990, managed forests sequestered about 50% of total CO_2 emissions. In 1990–1994, GHG emissions dropped markedly due to restructuring and loss in production in many sectors of industry and collective farming.

CO_2 concentrations decreased by 40% in the years 1990–1994. The main CO_2 emission source is the energy sector (fossil fuels combustion) it was in a crisis in 1992 and 1993. In 1994, a certain stability was observed in CO_2 emissions, and some increase was predicted for 1995.

Cattle farming is the main CH_4 emitter. Over the period 1990-1994, CH_4 concentrations decreased by 30%. A certain reduction in CH_4 emissions is anticipated for 1995.

Road transport accounts for significant portion of NO_x, CO and NMVOC emissions. A critical period in the sector was observed in 1991–1992. Since 1993, transport-induced pollution has been increasing.

N_2O is emitted mainly due to agricultural activities (use of mineral fertilizers) and firewood combustion.

Data reported from the EMEP MSC-East for 1991–1992 shows that Latvia's contribution to the pollution of the neighboring states was several times lower than transboundary emissions to Latvia from emitting countries. Taking the ongoing economic crisis into consideration, transboundary pollutant concentrations will be increasing as compared to locally emitted pollutants.

7.3 Goals in Emissions Reduction in Latvia

1. To encourage the neighboring states to reduce transboundaryy pollutant transport.
2. To have CO_2 emissions and the other GHG concentrations not included in the Montreal Protocol decrease to 1990 levels by the year 2000.
3. To have GHG concentrations resulting from national activities decrease to 1988 levels by the 1999.
4. To reduce NO_x concentrations in 1995 and in subsequent years to values lower than those on record in 1987.
5. To reduce total sulfur oxide concentrations to values lower than those on record in 1980 by the year 2000.

Projection of GHG emissions (*Forecast...,* 1995) in 2000 (second scenario corresponding to medium economic growth rates and maximum growth in gross domestic product after 1996 by 6% per annum) is as follows (thousands metric tons): CO_2 — 16956 (vs 22976 in 1990), CO_2 uptake by forests — 8940 (vs — 14300 in 1990), CH_4 — 114.15 (vs 159 in 1990), N_20 — 1.43 (vs 2.38 in 1990), NO_2 — 52.48 (vs 90.13 in 1990), CO — 278.23 (vs 363.12 in 1990), NMVOC — 39.19 (vs 62.7 in 1990).

The data show that CO_2 emissions will decrease by 26%, CH_4 — by 28%, and N_2O — by 40% in 2000 as compared to 1990.

8. Conclusions

1. Long-term observations and emissions data from local sources indirectly testify that atmospheric pollution level is formed not so much by local sources as by regional ones.
2. Maintenance of the National Cadastre of anthropogenic emissions provides a basis for the elaboration, execution and updating of the national program; catalogued measures to mitigate climate change implications should be accompanied by regular GHG measurements in the atmosphere.
3. The establishment of concurrent ozone concentration and greenhouse gas measurements and meteorological observations to trace interactions of different atmospheric characteristics is highly efficient.

References

Climate Reference Book, 1968: *History and Description of Stations and Posts in Latvia.* Riga (in Russian).

Environmental Pollution Conditions in Latvia, 1991. Annual Report, 1992. Hydrometeorological Agency of the Council of Ministers of the Republic of Latvia, Riga.

Environmental Pollution in Latvia, 1992. Annual Report, 1993. Hydrometeorological Agency of the Council of Ministers of the Republic of Latvia, Riga.

Environmental Pollution in Latvia, 1993. Annual Report. 1993. Latvian State Hydrometeorological Agency, Riga.

Environmental Pollution in Latvia, 1994. Annual Report, 1995. Latvian State Hydrometeorological Agency, Riga.

Forecasts of Greenhouse Gas Emissions in Latvia, 1995. Ministry of Environmental Protection and Regional Development of the Republic of Latvia, Riga.

Lyulko, I., Dubrovskaya, R., and *Grinman, A.,* 1993: The Works in the Republic of Latvia within the Frames of the EMEP Programme. EMEP Workshop on the Control of Photochemical Oxidation in Europe, Provo, Finland.

Short Review of the Environmental Pollution Conditions in Latvia in 1989, 1990. Latvian Hydrometeorological Agency, Riga (in Russian).

Short Review of the Environmental Pollution Conditions in Latvia in 1990, 1991. Latvian Hydrometeorological Agency, Riga (in Russian).

Summary of the First National Communication under United Nations Framework Convention on Climate Change, 1995. Ministry of Environmental Protection and Regional Development of the Republic of Latvia, Riga.

Zirnitis, A., 1983: *Climate of Latvian SSR.* Latvian State Publishing House, Riga (in Latvian).

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

GHG Emissions from the Power Generation Sector, Mobile Sources, and the Residential Sector in Kazakhstan

E. Monokrovich, N. Inozemtseva, and **D. Danchuk**

Kazakh Scientific-Research Hydrometeorological Institute,
Seifullin pr. 597, 480072, Almaty, Kazakhstan

Abstract—This article provides information on the main greenhouse gas (GHG) sources and estimates of emissions for Kazakhstan in 1990 as well as the methods used to calculate these emissions and the uncertainties associated with them. 1990 is taken as the base year, because under the Framework Convention of Climate Change, countries must submit inventories of GHG emissions for the year 1990.

In 1990, energy-related carbon dioxide (CO_2) emissions in Kazakhstan totaled 189.1 million tons or 51.6 million metric tons of carbon equivalent (MMTCE).

The power generation sector contributes a major portion of the total CO_2 emissions (25.4 MMTCE, or 48%), resulting from the intensive use of fossil fuels in power generation. Other major contributors are the mobile sources (8.6 MMTCE, or 16%) and the residential sector (8.5 MMTCE, or 16%).

Key-words: GHG emissions, carbon dioxide, power generation, mobile sources, fossil fuels.

1. Introduction

1.1 Objectives

Major greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFC). In addition, photochemically important gases, such as carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane volatile organic compounds (NMVOCs), contribute indirectly to the greenhouse effect.

Human activities are causing an increase in atmospheric concentrations of GHG, especially in CO_2, CH_4, and N_2O. The increase in GHG concentrations can cause signifficant global climate change (*EPA,* 1994). In this study we have compiled an emissions inventory that identifies and quantifies the primary sources of GHG in Kazakhstan. Systematically and consistently estimating emissions at the national level is a prerequisite for evaluating the cost-effectiveness and feasibility of pursuing possible mitigation strategies and implementing emissions reduction technologies.

1.2 Principal Characteristics of Kazakhstan

Kazakhstan is situated in the center of the Eurasian continent, between parallels 41° and 56° North Latitude and meridians 46° and 88° East Longitude. Kazakhstan is landlocked and is bordered by Russia, China, Uzbekistan, Kyrgyzstan, and Turkmenistan. The country is divided into Betpaqdala (desert), Saryarqa (Kazakh upland), Torghay and Ustyurt plateaus, southern mountains, and lowland plains. The altitude varies from 4,000 meters above sea level in the high mountain ridges to minus 30 meters in the Caspian lowland. Climate in Kazakhstan is moderate continental.

Kazakhstan has an area about 2.72 million square kilometers, inhabited by a population of about 17.5 million. The country has a proportion of energy-intensive industry because of its strong natural resource base.

2. Methods

Theoretically, if the carbon content of a fuel and its combusted quantity is known, the resulting volume of CO_2 can be estimated with a high degree of precision.

GHG emissions from main sources in Kazakhstan were estimated using methodologies that are consistent with the IPCC Draft Guidelines (*IPCC/OECD,* 1994). For comparing national inventory reports, the IPCC recommended using the 'top-down' approach to estimating CO_2 emissions from energy consumption. Total carbon release is estimated by multiplying the amount of fuel consumed by the carbon content in each fuel. The estimated amount of unoxidized carbon ranges from approximately 1% for oil and coal to 0.5% for natural gas. We assumed that 5% of fuel coal is not oxidized except for the power generation sector. The contribution of different gases to the greenhouse effect was evaluated using the total global warming potentials (GWP).

3. Input Data

Approximately 92% of Kazakhstan's electric power is produced by the combustion of fossil fuels. The remaining 8% comes from hydropower (*Chokin et al.,* 1990). The amount of carbon in fossil fuels varies significantly depending on the fuel type. For example, coal contains 39–48% carbon, while petroleum has 85% and natural gas has 75% carbon (*Power...,* 1979).

The data collected in Kazakhstan are more of the 'bottom-up' or technology-specific nature. Emissions estimates from energy consumption are based primarily on information from the Ministry of Energy of Kazakhstan. Emissions of NO_x and CO were taken directly from the government statistical sources.

4. Results and Discussion

4.1 Main Results

Based on a recent computation of 1990 Kazakhstan GHG emissions according to the IPCC guidelines, the Kazakhstan net emissions totaled 64 million metric tons of carbon equivalent. The largest share, about 80%, comes from CO_2.

The main source of CO_2 is the energy sector, which accounts for 98% of emissions. The other sources are represented by various industrial processes. GHG emissions have been grouped into three sectors:

- Power generation
- Mobile sources
- Residential.

The major fuel source categories considered in this article are coal, fuel oil, natural gas, wood, and other fuels[1]. Biomass fuels are not included in the national CO_2 balance (*IPCC/OECD,* 1994).

Coal from all sectors of the economy accounted for about 65% of total Kazakhstan energy-related CO_2 emissions; petroleum products for 26%; and natural gas for 9%. The 1990 Kazakhstan GHG inventory is presented in *Table 1*. CH_4 and N_2O represent a much smaller portion of total emissions than CO_2. Kazakhstan emissions were slightly offset by an uptake of carbon in Kazakhstan forests of 1.094 MMTCE, or 2% of net Kazakhstan emissions.

Table 2 illustrates the relative contributions of the primary GHG source categories to total Kazakhstan emissions in 1990. CO_2 emissions accounted for the largest share of emissions: 52.753 MMTCE, or 82.37%. Methane accounted for 17.37% of total emissions, including contributions from landfills and agricultural activities, among others. The other gases were less important, with N_2O emissions comprising 0.26% of total emissions.

In 1990, Kazakhstan emitted a total of 51.566 MMTCE of CO_2 from fossil fuel combustion. The energy-related activities producing these emissions included the generation of electricity and steam production at 37 heat power plants (HPPs) and 14 large boiler-houses (25.383 MMTCE, or 49.22%), gasoline consumption in automobiles and other vehicles (8.615 MMTCE, or

---

[1] These other fuels include diesel fuel, gasoline, LPG, condensed gas, fuel for residential stoves, straw, dry stalks, and bolls of cotton plants or guzapaya.

16.71%), heating and cooking in residential buildings (8.498 MMTCE, or 16.48%), and other (9.070 MMTCE, or 17.59%).

Emissions of the photochemically important gases CO, NO_x, and NMVOCs were 3045, 827, and 260 Gg (molecular basis), respectively.

Table 1. GHG emissions sources in Kazakhstan in 1990

Emissions source categories	CO_2 (MMTCE)	CH_4 (MMTCE)	N_2O (MMTCE)	CO (Gg)	NO*x* (Gg)	NMVOC (Gg)	GHG total (MMTCE)
Power generation	25.383	–	0.086	7.0	247.3	–	25.469
Mobile sources	8.615	0.033	0.045	2016.3	474.0	260.3	8.693
Residential	8.498	0.001	–	233.5	58.1	–	8.499
Others	10.257	11.088	0.038	788.6	47.8	–	21.383
Total (net) national emissions	**52.753**	**11.122**	**0.169**	**3045.4**	**827.2**	**260.3**	**64.044**

Table 2. Structure of GHG emissions in Kazakhstan (%)

GHG source categories	CO_2	CH_4	N_2O	CO	NO_x	NMVOC	GHG emissions total
Power generation	48.12	–	50.89	0.23	29.90	–	39.77
Mobile sources	16.33	0.30	26.63	66.21	57.30	100.00	13.57
Residential	16.11	0.01	–	7.67	7.02	–	13.27
Others	19.44	99.69	22.49	25.89	5.78	–	33.39
Total (net) national emissions	**100**	**100**	**100**	**100**	**100**	**100**	**100**

4.2 Power Generation Sector

Carbon dioxide is emitted when carbon-based fuels are burned. Emissions estimates are made on the basis of the amounts of fuels used and their carbon contents.

The quantities of fuel expressed in joules have been calculated using the net caloric values (NCV) of the fuels. The top-down approach results in CO_2 emissions of 20.489 MMTCE from coal combustion in the power generation sector (*IPCC/OECD, 1994*).

The basic bottom-up calculation procedure for coal is represented by the following equation:

$$M\ (CO_2) = B_{taf} \times R \times F_{co} \times 3.67,$$

where M (CO_2) is the mass of CO_2 emissions (tonnes), B_{taf} is the mass of coal (actual tonnes), R is the portion of carbon in the working mass of coal (relative units), F_{co} is the portion of carbon oxidized (relative units), and 3.67 is the molecular weight ratio of CO_2 and C (relative units) (*IPCC/OECD, 1994*). Carbon emissions estimates from the bottom-up approach totaled 20.872 MMTCE.

The two alternative approaches can produce relative estimates that are comparable within a few percentage points. The major difference between these methods lies in the energy data used to derive carbon emissions (actual reported consumption in the bottom-up methodology and 'apparent' consumption derived from the fuel balance in the top-down methodology). *Table 3* summarizes the differences between the two methods in CO_2 emissions for coal in the power generation sector. The bottom-up methodology estimate of CO_2 emissions from coal combustion in the power generation sector in Kazakhstan was 1.8% higher than that for the top-down methodology.

Nitrous oxide emissions from stationary sources were 0.124 MMTCE in 1990 (73.37%). The largest proportion of N_2O emissions comes from coal combustion, accounting for about 94% of total N_2O emissions in 1990. It is important to note, however, that this gas is currently not regulated in Kazakhstan.

Nitrous oxide emissions were estimated using IPCC-recommended emissions factors and Kazakhstan fossil fuel and wood fuel consumption data. The results were obtained by multiplying the appropriate emissions factors (by sector and fuel type) by the appropriate Kazakhstan energy data. The emissions factors used were 0.1 g N_2O/GJ for gas, 0.6 g N_2O/GJ for oil, and 1.4 g N_2O/GJ for coal in all sectors. The N_2O emissions from biomass burned in ovens, cook stoves, and small boilers in the residential sector were also calculated according to IPCC recommendations.

Table 3. Comparison of different emission estimation approaches

Coal Basin	CO_2 emissions ('top-down' approach) Gg	CO_2 emissions ('bottom-up' approach) Gg	Difference in % of 'bottom-up' approach
Kuznetsk	3862	3631	+6.4
Ekibastuz and Maikuben	56065	58245	-3.7
Karaganda	10280	9876	+4.1
Koocheke	284	278	+2.2
Borlinsk and Shubarkul	3315	3130	+5.9
Kyrghyz	1277	1323	-3.5
Tajik	18	19	-5.3
Uzbek	27	29	-6.9
Total	**75128**	**76531**	**-1.8**

4.3 Mobile Sources and Residential Sector

Energy used for mobile sources and domestic purposes is a significant source of GHG. Mobile sources contribute substantially to CO_2 emissions, accounting for about 17% of Kazakhstan emissions. Virtually all of the energy consumed in this sector comes from petroleum-based products.

Emissions from mobile sources are estimated by transportation fuel consumption, where several major fuel types, including diesel fuel, motor gasoline, aircraft gasoline, and kerosene are considered. Nearly 41% of the emissions result from gasoline consumption in automobiles and other vehicles, including diesel fuel.

Tables 1 and 2 clearly show that fuel consumption accounts for the majority of emissions of CO, NO_x and NMVOCs. In fact, motor vehicles that burn fossil fuel are the largest source of CO emissions in Kazakhstan, contributing about two-thirds (66.21%) of all Kazakhstan CO emissions in 1990. Motor vehicles also emit 57.30% of total Kazakhstan NO_x emissions and all NMVOC emissions. N_2O emissions from mobile sources totaled 0.045 MMTCE in 1990 (26.63% of the total).

The residential sector accounts for about 16% of total CO_2 emissions. Stationary combustion in the residential sector is believed to be a small source of CH_4 and N_2O. Methane emissions from the residential sector in 1990 accounted for about 0.78% of total Kazakhstan CH_4 emissions, while N_2O emissions from the residential sector accounted for 6.51% of all N_2O emissions. Stationary combustion in the residential sector is a minor source of nitrogen oxides (NO_x) and carbon monoxide emissions. 1990 emissions of NO_x from the residential sector represented 7.02% of national NO_x emissions, and CO emissions from the residential sector contributed 8.02% to the national CO total.

Carbon dioxide emissions from biomass have been estimated separately from fossil fuel-based emissions and are not included in the Kazakhstan totals. In 1990, CO_2 emissions from woody biomass were about 0.9 MMTCE, and the Kazakhstan residential sector accounted for all these emissions.

4.4 Uncertainty of Emissions Estimates

The current Kazakhstan emissions inventory has several weaknesses. Many of the categories of GHG emissions can be estimated only with large ranges of uncertainty. The IPCC Guidelines, however, require that users provide a single point estimate for each gas and emissions category.

Some of the current estimates, such as those for CO_2 emissions from energy-related activities, are considered accurate; their possible error is not more than 5%. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limit the scope or accuracy of the inventory; possible error associated with these categories is about 20%. To quantify uncertainty, *Table 4* provides the ranges (the numerator) and average values (the denominator) of specific emissions (emission tonnes per fuel tonnes) from mobile sources.

Table 4. Uncertainty of emission estimates for mobile sources

GHG	Specific emissions, t/t of fuel		
	Gasoline	Diesel fuel	Gas
Carbon oxide	0.250–0.800 / 0.420	0.006–0.200 / 0.047	0.040–0.310 / 0.090
Hydrocarbons	0.023–0.100 / 0.046	0.004–0.050 / 0.019	0.020–0.040 / 0.021
Nitrogen oxides	0.016–0.040 / 0.027	0.018–0.045 / 0.033	0.008–0.040 / 0.016

5. Conclusions

The calculation of emissions in Kazakhstan was carried out using emissions factors from the IPCC Guidelines and activity data from national statistics.

According to the 1990 inventory, CO_2, CH_4, and N_2O accounted for 82.4%, 17.4%, and 0.2% of all Kazakhstan anthropogenic emissions (in MMTCE), respectively.

Kazakhstan emissions of CO_2, the principal anthropogenic GHG, are divided among the power generation sector (48%), mobile sources (16%), the residential sector (16%) and other sectors (20%).

Emissions estimates of N_2O historically have not been calculated in Kazakhstan. Emissions estimates for this gas were calculated using the IPCC-recommended methodologies and emissions factors.

Carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds are also included in the Kazakhstan inventory.

Fossil-fueled motor vehicles are the largest source of CO emissions in Kazakhstan. In 1990, CO emissions from mobile sources contributed about 66% of all Kazakhstan CO emissions. Motor vehicles also emit about 57% of total Kazakhstan anthropogenic NO_x and all NMVOCs emissions.

References

Chokin, S.C. et al., 1990: *Energy and Electrification of Kazakhstan* (in Russian). 'Gylym', Almaty.

EPA, 1994: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1993*. EPA, Washington, DC, USA.

IPCC/OECD, 1994: *Greenhouse Gas Inventory Reference Manual*, Vol. 3, Paris.

Power Fuel in the USSR. Reference Book, 1979: 'Energy', Moscow, (in Russian).

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

GHG Emissions from Agriculture, Land Use Change and Forestry in Kazakhstan

E. Monokrovich, O. Pilifosova, E. Gossen, and **A. Startsev**

Kazakh Scientific-Research Hydrometeorological Institute,
Seifullin pr., 597, 480072 Almaty, Kazakhstan

Abstract—A central element to any study on climate change is a compilation of the national emission inventory. The aim of this paper is to present the emissions and removals estimates for the agriculture and land use change and forestry sectors in Kazakhstan. Greenhouse gas emissions estimates for the agriculture sector were calculated using the IPCC Guidelines for National Greenhouse Gas Inventories. The land use change and forestry sector emissions estimates were determined using a methodology that offers a slight variation on IPCC methods. Emissions estimates for 1990 through 1993 are presented, with 1990 referred to as the base year. The agricultural sector accounted for approximately 45 percent of total Kazakhstan methane emissions. Within this sector, the majority of methane emissions are due to domestic livestock enteric fermentation and manure management. Other agricultural activities contributing to GHG emissions include rice cultivation, soil management and fertilizer use. The net CO_2 flux associated with the land use change and forestry sector resulted in a carbon uptake of 3,963 Gg or 1.08 million metric tones of carbon equivalent (MMTCE), which equals about 2 percent of the total CO_2 emissions in Kazakhstan.

Key-words: greenhouse gas emissions, inventory, domestic livestock, manure management, forestry, Kazakhstan.

1. Introduction

The Republic of Kazakhstan is about 2,717,000 km^2 and has a population of over 17 million. The Republic consists of 19 regions, 220 districts, over 80 cities and towns. About 40 percent of Kazakhstan is made up of desert land. Kazakhstan's remaining territory consist of about 27 percent forest-steppe and steppe lands, 22 percent semi-desert lands, and 11 percent mountains.

The sowing areas of Kazakhstan exceeds 35 million hectares, including about three million hectares of irrigated land. Total yields of grain are estimated to be approximately 25 to 30 million tons per year, some of which is exported. Sheep breeding, supported by vast expanses of both desert and semi-desert pastures, is the leading branch of animal husbandry in Kazakhstan. Cattle livestock (about 9 million) and pig, camel and horse breeding also contribute to the agricultural industry in Kazakhstan.

Forested areas make up about 9,648,000 ha (hectares), or about 3.6 percent of the total territory in Kazakhstan. About 4.7 million ha of Kazakhstan's forested lands are covered with saksaul, an undersized drought-resistant tree growing predominantly in desert and semidesert areas. Coniferous forests make up about 1,800,000 ha of total forested lands, while deciduous woods and shrubs grow on remaining forested areas. Agricultural lands in Kazakhstan are about 200 ha, all of which are subjected to severe ecological damage due to agricultural activities.

There is much concern surrounding the consequences of increased emissions of CO_2 and other greenhouse gases due to anthropogenic activities and associated climate change. With already extremely vulnerable ecosystems, Kazakhstan finds the need to address climate change issues particularly urgent.

The Republic of Kazakhstan is one of more than 150 countries to sign the United Nations Framework Convention on Climate Change. The Kazakhstan Government supports international cooperation on climate change issues, making participation in the first round of the U.S. Country Studies Program a priority. Through the Country Studies Program, Kazakhstan began the emissions inventory process to identify and quantify major sources and sinks of greenhouse gases.

This article presents greenhouse gas emissions estimates for the agriculture and forestry and land use change sectors, calculated as part of the Kazakhstan GHG Inventory. Emissions estimates for the land use change and forestry sector were derived using a methodology that slightly departs from IPCC emissions estimate guidelines.

2. Methods and Results

1990 emissions estimates of six GHG from various sources in Kazakhstan are presented in *Table 1*. In compliance with IPCC guidelines, emissions estimates are expressed in gigagrams (Gg). Emissions estimates not included in the total are indicated in parentheses. *Fig. 1* presents total emissions estimates of all gases by source. Calculations are presented in units of million metric tones of carbon-equivalent (MMTCE). To express estimates in MMTCE, emissions are multiplied by the Global Warming Potentials (GWP) that reflect relative potencies of different gases. Following the recommendations of the IPCC (*IPCC*, 1992) a GWP of 22 was used for methane, 270 for nitrous oxide and 1 for carbon dioxide.

As demonstrated in Table 1, 195414.1 Gg (more than 200 million tones) of GHG are emitted in Kazakhstan annually. Based on this emissions estimate, GHG emissions per capita exceed 11 tones a year.

Table 1. GHG Emissions in Kazakhstan in 1990, Gg/year

	Emission Sources (sectors)	CO_2	NO_2	CH_4	CO	N_2O	NMVOC
1.	Energy (Module 1)	189,078.0	827.2	909.6	2,911.4	2.3	260.3
2.	Industrial Processes (Module 2)	4,349.0			134.0		
3.	Agriculture (Module 4)	(90,000)	1,052	833.5		10.0	
4.	Waste (Module 6)			111.5			
5.	Land Use Change and Forestry (Module 5)	-3,963.0		0.9	7.7		
	Total	**189,464.0**	**827.2**	**1,855.5**	**3,053.1**	**2.3**	**260.3**

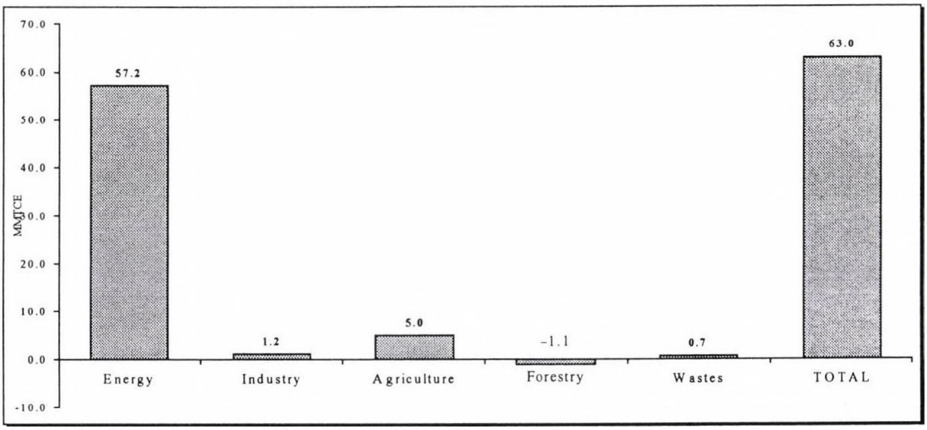


Fig. 1. Total Kazakhstan emissions by source in 1990 (million metric ton of carbon equivalent). Energy = 57.2; Industry = 1.2; Agriculture = 5.0; Forestry = –1.1; Wastes = 0.7; Total = 63.0

3. Agriculture

Agricultural activities produce 5 MMTCE, or approximately 8 percent of total GHG emissions in Kazakhstan (Fig. 1). Methane (CH_4) makes up the largest percentage of total GHG emissions due to agricultural activities. Other GHG emissions from the agricultural sector include nitrous oxide (N_2O) and nitrogen dioxide (NO_2) (Table 1).

While the IPCC recommends that field burning of agricultural crop wastes be included in the GHG emissions inventory, crop waste burning is not practiced in Kazakhstan. Therefore, emissions from this activity are not included in the Kazakhstan GHG Inventory. CO_2 emissions from organic substances in the agricultural sector are also not included in the Kazakhstan Inventory.

3.1 Methane Emissions

The agricultural sector is responsible for more than 45 percent of total methane emissions in Kazakhstan. Domestic livestock, manure management and rice cultivation are all sources of methane within this sector.

In 1990 enteric fermentation in domestic livestock and manure management together were responsible for 94.3 percent of methane emission from agricultural activities (see *Fig. 2*). Methane produced by enteric fermentation in livestock accounts for 76.1 percent of total CH_4 emissions from the agricultural sector. Methane emissions from this source vary depending on the type, age and productivity of the livestock.

Methane emissions from manure management occur with decomposition under anaerobic conditions. Emissions from this source make up about 18.2 percent of total methane emissions from agricultural activities.

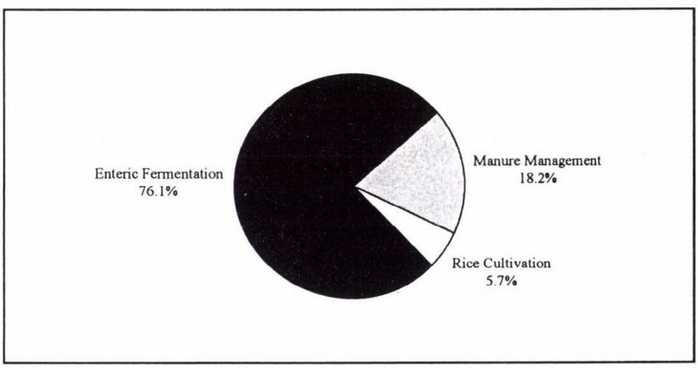


Fig 2. Methane emissions from agriculture.
Enteric fermentation = 76.1 %; Manure management = 18.2 %; Rice cultivation = 5.7%

CH_4 emissions were estimated using the IPCC methodology (*IPCC/OECD*, 1994). According to this methodology, CH_4 emissions for both enteric fermentation and manure management are determined by multiplying the number of animals within each livestock type by methane emissions factors. Emissions factors are provided for both developed and developing countries and for different regions and climate regimes. Emissions factors for enteric fermentation and manure management, as well as emissions estimates for 1990, are based on these factors and are presented in *Table 2*.

Animal population statistics for each livestock type are determined by an agricultural sector census and are included in the State Statistic Accounts (*Kazakhstan...*, 1991). Total methane emissions from all animal types are 774.7 Gg or 4.6 MMTCE. Emissions estimates for 1991 and 1992, while fairly consistent with 1990 emissions, indicate slight reductions in emissions due to declining animal populations.

Methane emissions from rice cultivation make a relatively small contribution to total CH_4 agricultural emissions, representing approximately 5.7 percent (Fig. 2). Anaerobic decomposition of organic material in flooded rice fields produces methane that escapes into the atmosphere through the rice plants. Methane emissions from rice cultivation in Kazakhstan were derived using the methodology recommended by the IPCC (*IPCC/OECD*, 1994). To calculate emissions, a daily emissions factor was multiplied by the total flooded area harvested and the number of days of flooding during the growing season.

The aggregate emissions factor from Kazakhstan rice fields, based on the average temperature of the growing season and irrigation regimes, is equal to 4.22 kg/ha/day. The total area of harvested rice is on average about 120,000 ha. The average duration of a growing season for all rice species cultivated in Kazakhstan is about 115 days (*Kazakhstan...*, 1991). Thus, annual methane emission from flooded rice fields in 1990 was calculated as follows:

$$4.22 \times 120000 \times 115 = 58{,}236{,}000 \text{ kg} = 58.2 \text{ Gg}.$$

Total methane emission from agriculture in 1990 is 833.5 Gg or 5,001 MMTCE.

3.2 Carbon Dioxide (CO_2) Emissions

Between 5 to 8 tones of CO_2 is released into the atmosphere from 1 ha of sowing area as a result of organic substances decay (*Rubenzam* and *Raue*, 1969). It is assumed that CO_2 release is at the lower end of this range due to low productivity levels of cereals and other culture in Kazakhstan. The Academy of Agriculture estimates the total sowing area is about 18 million ha. Based on these estimates, about 90 million tones or 90,000 Gg of CO_2 were emitted. Since the total amount of CO_2 emitted from organic decay is absorbed by vegetation, this emissions estimate is not included in the overall GHG emissions estimate for the Republic of Kazakhstan.

3.3 Nitrogen Dioxide (NO_2) Emissions

In Kazakhstan, organic fertilizers are applied to fallow for cereal cultivation. Organic substance decay and application of fertilizers for grain cultivation result

Table 2. Methane emissions from domestic livestock in 1990

Animals	Population	Enteric fermentation		Manure management		Total emissions
		Emission factor	Emissions	Emission factor	Emissions	
	(1000s)	(kg/head/year)	(Gg/year)	(kg/head/year)	(Gg/year)	(Gg/year)
Non-dairy cattle	6,389.3	44	281.1	1.0	6.4	287.5
Dairy cattle	3,368.0	56	188.6	16.0	53.9	242.5
Sheep and goats	36,660.5	5	183.3	0.16	5.9	189.2
Pigs	2,976.1	1	3.0	4.0	11.9	14.9
Horses	1,666.4	18	30.0	1.6	2.7	32.7
Camels	143.0	46	6.6	1.9	0.3	6.8
Poultry	59,898.8	0	0.0	0.018	1.1	1.1
Total			**692.6**		**82.1**	**774.7**

in the release of 800 kg ammonia or 330 kg nitrogen into the atmosphere. 250 kg of nitrogen are assimilated from the air each year (*Rubenzam* and *Raue,* 1969). Thus, 263 kg of NO_2 (80 kg of nitrogen) are released into the atmosphere from 1 ha of fallow. The Academy of Agriculture estimates that total fallow is approximately 4 million ha. The NO_2 emissions from this area are about 1,052 million tones or 1052 Gg per year.

3.4 Nitrous Oxide (N_2O) Emissions

The IPCC emissions factor for N-N_2O is 0.01 of the amount of applied nitrogen by vegetation. This value was multiplied by 44/28 (ratio between nitrous oxide and nitrogen molecular weights). Based on this emissions factor and the total area used for fallow, total N_2O emission are 10 Gg/yr or 736.4 MMTCE.

4. Land Use Change and Forestry

Land use and forest management activities change the natural balance of carbon dioxide, as well as other greenhouse gases. The most important activities in this sector are the following:

- Clearing an area of forest to create cropland,
- The conversion of grasslands and pastures into arable lands,
- Restocking logged forest,
- Forest exploitation, including logging, afforestation, collection of fuel, wood, and forest cultivation.

Carbon dioxide emissions and absorption from forested areas in Kazakhstan were evaluated using a methodology that varies slightly from the one recommended by the IPCC. For example, the IPCC methodology recommends that emissions from forest clearing be included in emissions estimates for the land use change and forestry sector. However, in the submodule, 'CO_2 Emissions from Forest and Grassland Conversion', emissions from forest clearing were not calculated because forest clearing is not practiced in Kazakhstan. Instead, emissions from large forest fires were included in estimates of carbon dioxide emissions.

Large forest fires over the last 25 years were considered in the carbon emissions estimate. The most recent occurrence of such a fire was in 1974, when more than 10 million m^3 of timber was destroyed. As a result, areas covered with Siberian fir (*Abies sibirica*) and larch forests (*Larix sibirica*) decreased by 0.2 and 0.6 percent respectively and total wood stocks decreased by about 0.7 percent. The distribution of biomass was as follows: 0.3 biomass was burned, 0.15 was removed by sanitary clearing, and 0.55 was refuse wood and biomass residues.

CO_2 emissions from burning of aboveground biomass were estimated to be 304 Gg/year, with 67 percent due to on-site burning and 33 percent from off-site burning. The CO_2 emissions from decomposed post-fire residue were estimated to be 360 Gg. Total CO_2 emissions from fires were estimated to be 664 Gg per year. Non-CO_2 annual average emissions from forest fires were estimated as follows: CO emissions are 7.74 Gg; CH_4 emissions are 0.88 Gg (64 MMTCE); NO_2 emissions are 0.143 Gg and N_2O emissions are 0.006 Gg.

Using the IPCC methodology, average annual carbon dioxide uptake by managed forests is equal to 4627 Gg or 2.7 MMTCE of CO_2. Thus the net carbon dioxide uptake in 1990 is equal to 4627 - (360 + 304) = 3963 Gg of CO_2 (1. 08 MMTCE). This value constitutes approximately 2 percent of total CO_2 emissions and about 1.3 percent of total GHG emissions in Kazakhstan.

5. Conclusions

In 1990 agricultural activities in Kazakhstan resulted in emissions of 833.5 Gg (5 MMTCE), comprising approximately 8 percent of total GHG emissions. Methane emissions from agricultural activities are equal to approximately 45 percent of total methane emissions in Kazakhstan. Enteric fermentation in domestic livestock and manure management together account for the majority of agricultural methane emissions. About 1052 Gg of NO_2 and 10 Gg of N_2O are also emitted to the atmosphere due to agricultural activities. There are several sources of uncertainty, such as uncertainty connected with statistical data on animals population and uncertainty connected with using the default emission factors. Together all sources of uncertainty result in an overall uncertainty of 20% of the emissions estimate.

Using the IPCC methodology, the average annual carbon dioxide uptake from forest exploitation is estimated to be 4627 Gg CO_2 (2.7 MMTCE). Forest fires reduced the net carbon dioxide uptake in 1990 to 3963 Gg of CO_2 or 1.08 MMTCE.

References

IPCC, 1992: *Climate Change 1992: Supplementary Report to the IPCC Scientific Assessment* (eds.: *J.T. Houghton, B.A. Callender*, and *S.K. Varney*. Cambridge University Press, Cambridge, UK.

IPCC/OECD, 1994: IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 1-3. Intergovernmental Panel on Climate Change, Organization for Economic Co-Operation and Development, Paris.

Kazakhstan State Statistical Account for 1990, 1991: Kazinform, Alma-Ata (in Russian).

Rubenzam, E. and *Raue, K.*, 1969: *Agriculture* (in Russian). 'Kolos', Moscow.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3-4, July-December 1995

Fugitive Emissions from Polish Gas System

K. Steczko, J. Rachwalski, and **A. Froński**

Oil and Gas Institute, ul. Lubicz 25a, 31-503 Kraków, Poland

Abstract—The Polish gas system is briefly described. Main features are mentioned and present changes as well as future development programs are emphasised. Actual problems concerning greenhouse gas emissions inventory for Polish gas system have been pointed out and possibility of applying different tiers of inventory according to IPCC methodology has been assessed. Detailed inventory by emission sources and types has been chosen as the most methodologically legitimate and beneficial for future work. Polish gas system structure diagram has been prepared and greenhouse gas emission sources and emission types have been specified. The results of the inventory have been presented and discussed. The aggregate methane emission factor value calculated in this work for the Polish gas system has been situated in the middle of the range recommended by the IPCC for former USSR and Eastern European countries. It has been stressed that the usefulness of aggregate emissions factors for the entire system in future applications is limited in case of rapid transformation of the gas system under economy in transition. The need for establishing an international cooperation program for greenhouse gas emissions measurements from the gas system is stated.

Key-words: greenhouse gas (GHG), emissions, emissions factors, gas industry, economy in transition.

1. Polish Gas System Characteristics

The goal of this paper is to make some remarks regarding Poland's experience using the IPCC Guidelines to conduct the country's first greenhouse gas emissions inventory (*IPCC*, 1993a; *IPCC*, 1993b; *IPCC*, 1993c).

The Polish gas system has some specific features resulting from the following facts:

- The gas industry in Poland is well-established. Town gas works were founded in the second half of the XIX century and natural gas has been produced, distributed, and used since the beginning of the XX century.
- The gas system has been developed and operating for over 45 years under a centralised economy and gas prices have been subsidised.
- Because of the economic transition, the gas industry is presently undergoing deep transformation.

The following information briefly characterises the Polish gas system:

- The system consists of three independent subsystems that transmit and distribute high methane natural gas at approximately 75% of sales, low methane natural gas at approximately 23% of sales, and coke-oven gas at approximately 2% of sales.
- In 1992 the length of transmission pipelines was 14,000 km and the length of distribution pipelines was about 61,000 km.
- Twenty-seven compressor stations and 3,200 metering and regulation stations are supporting the gas transmission system.
- Four underground gas stores can store 0.6 bln m^3 of gas.
- Town gas is produced by the catalytic processing of natural gas.
- Low methane natural gas is processed by methane-nitrogen cryogenic separation.

The main changes of Polish gas system (*Fig. 1–5*) are as follows (*Findziński*, 1995; *Tokarzewski* and *Bednarski*, 1995):

- Coke-oven gas is being withdrawn from domestic usage and it is substituted by natural gas.
- Low methane natural gas from domestic sources is planned to be delivered mainly for industrial usage and cryogenic processing.

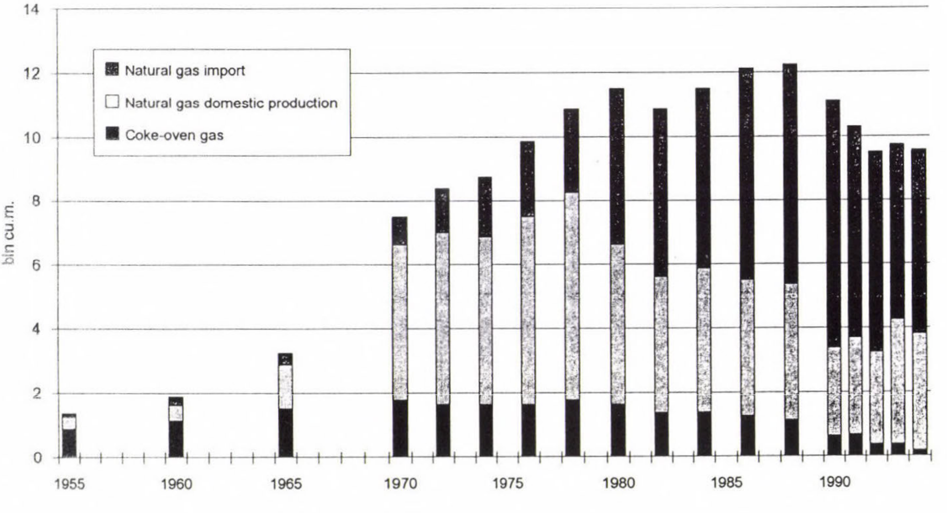


Fig. 1. Fuel gas supplies in Poland (1955–1994).

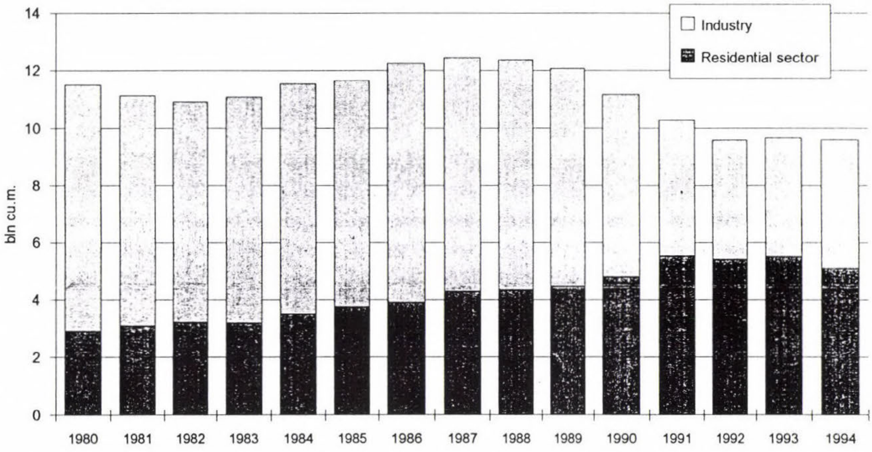


Fig. 2. Fuel gas consumption in Poland (1980–1994).

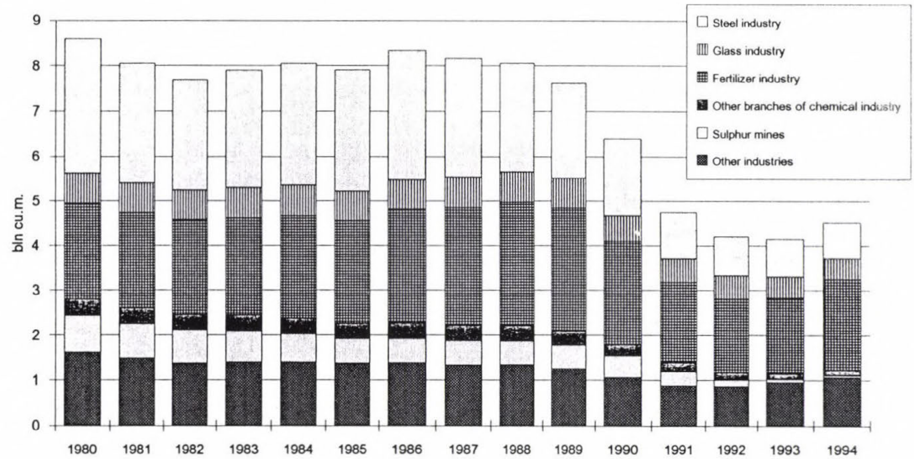


Fig. 3. Fuel gas consumption for industrial purposes in Poland (1980–1994).

- Due to economic transformation and gas-saving policy, gas consumption is decreasing. For example, in 1989 gas consumption was at 13 bln m^3, while in 1992 gas consumption was at 9.7 bln m^3.
- In 2010 the consumption is scheduled to increase to 27 bln m^3 in low scenario and 35 bln m^3 in high scenario. The forecasted rise in gas usage is one of the measures that will improve environmental conditions.

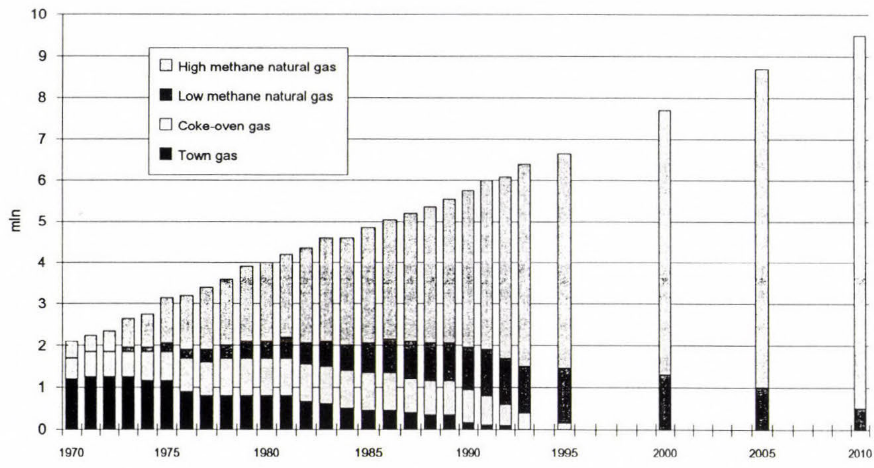


Fig. 4. Numbers of household consumers of gas in Poland (1970–2010).

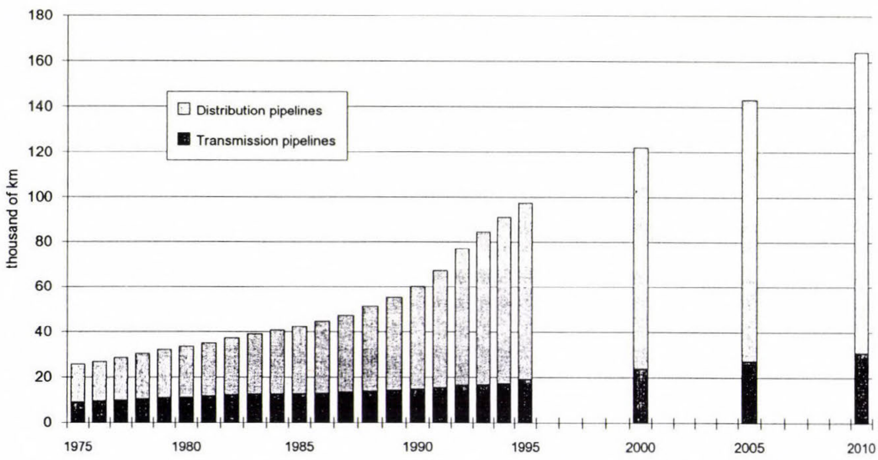


Fig. 5. Lenght of transmission and distribution pipelines in Poland (1975–2010).

- The structure of gas consumption is changing towards a higher share of residential and commercial sectors. Gas-fired power stations are considered the alternative to nuclear power generation.
- Gas transmission systems and gas distribution systems are being extended. For example, 14,000 km of transmission pipelines and 61,000 km of distribution pipelines were built in 1992, while 16,400 km of transmission pipelines and 68,000 km of distribution pipelines were built in 1994.

- Gas transmission and gas distribution networks are operating at less than full capacity.
- In order to increase gas storage capacity by 8–9 times, new underground gas storage facilities are planned.
- Modern technologies such as no-excavation methods for gas distribution network maintenance, the SCADA system, and hot tap method in gas pipelines assembling are being implemented.
- New materials are used in gas distribution sector (e.g., HDPE, MDPE, Rilsan).
- Drawbacks of the Polish gas system at present are the low accuracy of gas flow rate measurements (especially when the flow rates are lower than projected ones), the low number of gas measuring and data transmitting facilities in the gas system, and the lack of the cathodic protection of pipelines.

2. Methodology of Inventory Work

Polish gas industry reports relatively high values of unaccounted-for gas, but until 1993 any systematic studies concerning methane emissions from the gas system had not been conducted. In 1994 the first inventory work was done in the framework of the UNEP/GEF project, 'National studies on sources and sinks of greenhouse gases'. Because the IPCC Guidelines were used for the inventory, it was necessary to choose one from three possible Tiers.

The IPCC Tier 1 approach, 'Production based average emission factors', is the simplest tier and does not require any detailed information on the gas system except basic data on gas production and consumption. To obtain emissions values, the activity data are combined with average emissions factors recommended by the IPCC for the appropriate world region.

According to the IPCC, the aggregate emissions factors are much higher for the former USSR and Eastern European countries than for the rest of the world (*Table 1*). The resulting emission values obtained spread across such a broad range that the question arises whether this method is reasonable. In order to reduce the estimation uncertainty it would be necessary to choose only one emissions factor value from the range recommended by the IPCC, but for such a selection well-defined criteria are needed. Unfortunately these criteria are not available yet.

The IPCC Tier 2 approach is based on the gas mass balance in all sectors of the gas system including production, processing, storage, transportation and distribution. The simplest way to estimate emissions values is to assume that all reported gas losses result from emissions. This assumption is obviously not realistic and creates the maximum potential emissions values.

Consequently, in order to achieve the proper emissions assessment it is necessary to perform a detailed analysis of gas losses (*Cowgill*, 1994; *Meshkati* and *Groot*, 1994) taking into account the accuracy of gas measurements, the amount of gas used in the gas industry for technological purposes, gas thefts, and the gas marketing system. Such analysis is time-consuming and expensive and the results are only valid for the system under consideration. Because of ongoing changes in the Polish gas system (especially in gas measuring devices and in marketing) and changes in economy (influencing gas consumption and gas thefts), the results of an unaccounted-for gas analysis would only be valid for a short time period.

Table 1. Annual methane emissions estimation from Polish gas system

			1993	1994
Emissions factors recommended by IPCC (ton/PJ)	Transmission and distribution	min.	340	
		max.	715	
	Production	min.	218	
		max.	567.6	
Annual methane emissions calculated from activity data and IPCC factors (Gg)	Transmission and distribution	min.	107	105
		max.	225	222
	Production	min.	28	26
		max.	73	67
	Total	**min.**	**135**	**131**
		max.	**298**	**289**

Since the recognition of unaccounted-for gas in Poland is qualitative, the only way to assess emissions according to IPCC Tier 2 is to attribute the reported gas losses to gas emissions. Evidently this method is not correct.

The comparison of results obtained for the Polish gas system according to the IPCC Tier 1 and Tier 2 (reported gas losses) gives some idea on their convergence. Methane emissions calculated from activity data and limit values of aggregate emissions factors (IPCC Tier 1) make 35%–72% of gas losses reported for the year 1993 and 48%–108% of gas losses reported for 1994.

Since estimations of methane emissions obtained were not satisfactory according to the IPCC Tiers 1 and 2 because of their high and ill-defined uncertainty, it was decided to follow the IPCC Tier 3. This Tier is based on rigorous emissions source specification, specification of emission types, and usage of appropriate emissions factors. Applied emissions factors should be obtained as the result of field measurements, empirical correlations, or process simulation.

Difficulties related to this approach are serious, especially during the first estimation, but this Tier is definitely methodologically the most legitimate and gives the most accurate results. An additional advantage of the Tier 3 is the potential future benefit as the next estimations will need much less effort and their results will be more accurate when using this approach each year.

3. Results of Inventory Work

The first Polish GHG emissions inventory was generally based on the IPCC Tier 3. Unfortunately it was not possible to fulfil all the requirements of this approach; in some cases for small parts of the system reported gas losses were used if the detailed specifications of sources and types of emissions could not be obtained.

In order to perform the inventory, the following activities were completed:

- The gas system structure diagram was prepared (*Fig. 6*).
- Emission sources and types specifications were elaborated (*Table 2*). Approximately 200 different contributions should be taken into account in emissions estimation.

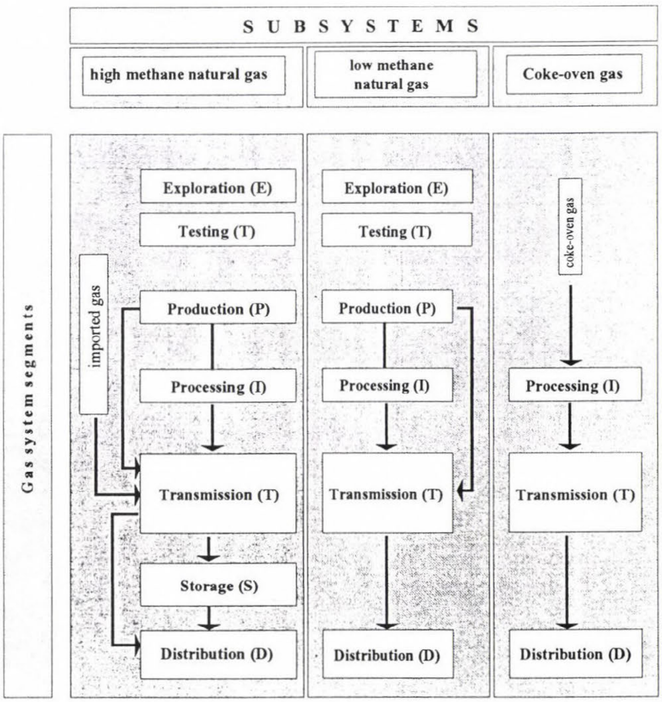


Fig. 6. Polish gas system diagram.

Table 2. Emission types and sources in all segments of the Polish gas system

Emission sources in the segment	**Emission types (according to IPCC)** **•emission during normal operation (N)** **•emission during routine maintenance (M)** **•emission during system upsets and accidents (A)**	
	Exploration (E)	
Exploration wells(E1)	gas escapes before well head installation fugitive emission from underground well equipment exhalation	E10 E11 E13
Incidentally gasified geological strata (E2)	exhalation	E24
	Wells testing (T)	
Wells under testing(T1)	gas blowdown	T10(N)
	Gas production and treatment (P)	
Gas wells (P1)	routine gas wells venting	P10(N)
	Gas production and treatment facilities:	
well heads (P2)	emission during normal operation emission during routine maintenance emission during upsets and accidents	P21(N) P22(M) P23(A)
pipelines gathering (P3)	emission during normal operation emission during routine maintenance emission during upsets and accidents	P31(N) P32(M) P33(A)
separators (P4)	emission during normal operation emission during routine maintenance emission during upsets and accidents venting	P41(N) P42(M) P43(A) P44(N)
gas heaters (P5)	emission during normal operation emission during routine maintenance emission during upsets and accidents	P51(N) P52(M) P53(A)
methanol tanks (P6)	venting emission during normal operation emission during routine maintenance emission during upsets and accidents	P60(N) P61(N) P62(M) P63(A)
gasoline collecting facilities (P7)	emission during normal operation emission during routine maintenance emission during upsets and accidents venting	P71(N) P72(M) P73(A) P74(N)
pneumatic devices (gas heaters, separators, dehydrators, pipelines) (P8)	venting emission during normal operation emission during routine maintenance emission during upsets and accidents	P80(N) P81(N) P82(M) P83(A)
glycol regenerators (P9)	venting emission during normal operation emission during routine maintenance emission during upsets and accidents	P90(N) P91(N) P92(M) P93(A)
gas dehydrators (P10)	emission during normal operation emission during routine maintenance emission during upsets and accidents	P101(N) P102(M) P103(A)
	Gas processing (I)	
gas processing plants (I1)	technological blowdown emission during normal operation emission during routine maintenance emission during upsets and accidents	I10(N) I11(N) I12(M) I13(A)
	Gas transmission (T)	
transmission pipelines (T1)	emission during normal operation	T11(N)

	emission during routine maintenance emission during upsets and accidents	T12(M) T13(A)
pneumatic devices (T2)	venting emission during normal operation emission during routine maintenance emission during upsets and accidents	T20(N) T21(N) T22(M) T23(A)
gate stations (T3)	emission during normal operation emission during routine maintenance emission during upsets and accidents	T31(N) T32(M) T33(A)
compressor stations (T4)	engine blowdown emission during normal operation emission during routine maintenance emission during upsets and accidents	T40(N) T41(N) T42(M) T43(A)
Gas storage (S)		
well heads (S1)	emission during normal operation emission during routine maintenance emission during upsets and accidents	S11(N) S12(M) S13(A)
pipelines (S2)	emission during normal operation emission during routine maintenance emission during upsets and accidents	S21(N) S22(M) S23(A)
gas preparation facilities (S3)	emission during normal operation emission during routine maintenance emission during upsets and accidents	S31(N) S32(M) S33(A)
pneumatic devices (S4)	venting emission during normal operation emission during routine maintenance emission during upsets and accidents	S40(N) S41(N) S42(M) S43(A)
compressor stations (S5)	engine blowdown emission during normal operation emission during routine maintenance emission during upsets and accidents	S50(N) S51(N) S52(M) S53(A)
Gas distribution (D)		
distribution pipelines (D1)	emission during normal operation emission during routine maintenance emission during upsets and accidents	D11(N) D12(M) D13(A)
services (D2)	emission during normal operation emission during routine maintenance emission during upsets and accidents	D21(N) D22(M) D23(A)
gas regulation and metering stations (D3)	emission during normal operation emission during routine maintenance emission during upsets and accidents	D31(N) D32(M) D33(A)

- System activity data were gathered. Some data were based on detailed inventory, while others were estimated using the gas system models.
- The emissions factors for individual sources and types of emissions were selected from the published values (*Meshkati* and *Groot*, 1994; *EPA*, 1993; *Lott*, 1994; *Campbell*, 1994) or were calculated from the available domestic data. When adopting the emissions factors from foreign measurements (*Meshkati* and *Groot*, 1994; *EPA*, 1993; *Lott*, 1994; *Campbell*, 1994; *Hewitt* and *Horn*, 1994; *Petersen* and *Sorensen*, 1994) their usefulness for Polish system was validated by either the conformity analysis of the gas system, the comparison with available domestic data, or the comparison of calculated emissions value with the reported gas losses.

- GHG emissions were calculated for individual subsystems as well as for the entire gas system and the aggregate emissions factors were found. The results of the estimation are shown in *Table 3*.

Total methane emissions from the Polish gas system were estimated to be 164 Gg/year in 1992 and the aggregate emissions factor for the entire system was found to be 473,000 kg/PJ (referring to energy consumption). This last value is situated nearly in the middle of the range recommended by the IPCC for the former USSR and Eastern Europe.

The uncertainty of the estimation was not determined but there are strong reasons to treat the obtained value of total emissions as higher than actual emissions. It should also be stressed that rapid development and profound transformation of the Polish gas system limit the future usefulness of aggregate emissions factors for the entire system.

Table 3. Estimation of GHG emissions from Polish gas system (in 1992)

	Activity data	Emissions estimates			Aggregate emissions factors		
		CH_4	NMVOC	CO_2	CH_4	NMVOC	CO_2
	PJ	Gg	Gg	Gg	kg/GJ	kg/GJ	kg/GJ
Gas (Total)	345.99	163.6724	5.2877	8.5457	0.4731	0.0153	0.0247
Production	113.78	7.4509	0.2614	0.0250	0.0655	0.0023	0.0002
Consumption	345.99	156.2215	5.0263	8.5207	0.4515	0.0145	0.0246

4. *Conclusions*

- The inventory of GHG emissions performed in 1994 for the Polish gas system gave the first approximation of an emissions value which is believed to be the upper limit value.
- The inventory which basically followed the IPCC Tier 3 approach enabled researchers to gain experience, to gather extensive data useful for future inventory work, and to prepare a strategy for future activities that must be undertaken in order to improve the accuracy of emissions estimation and to reduce overall emissions.
- The aggregate emissions factors are not accurate for countries like Poland in which deep and rapid transformation of the gas system occurs.
- International cooperation in the field of GHG emissions inventories from gas systems is desirable with two main goals: the elaboration of the international program for emissions measurements and realisation of this program in selected countries and the preparation of a database on emissions factors from gas system elements and establishing the criteria for applying these factors.

Acknowledgements—The inventory of GHG emissions from the Polish gas system was performed using IPCC Guidelines in the framework of the UNEP/GEF project, 'National studies of sources and sinks of greenhouse gasses'. The authors would like to thank all co-workers from the Oil and Gas Institute and the Polish Oil and Gas Company for their assistance in data collection and processing. The authors appreciate the scientific guidance of *Prof. E. Radwański* from FEWE and the technical support of National Foundation of Environmental Protection.

References

Campbell, L., 1994: Measurement of Methane Emissions from Underground Distribution Mains and Services. *International Workshop Environmental and Economic Impacts of Natural Gas Losses*, Prague, Czech Republic.

Cowgill, R. M., 1994: Methane Emission — Leakage, Sources and Unaccounted-for Gas. *International Workshop Environmental And Economic Impacts Of Natural Gas Losses*, Prague, Czech Republic.

EPA, 1993: *Anthropogenic Methane Emissions in the United States: Estimates for 1990.* Report to Congress, EPA 430-R-93-006.

Findziński, A., 1995: Warunki funkcjonowania i rozwoju górnictwa naftowego i gazownictwa w świetle potrzeb gospodarki narodowej. Konferencja naukowo-techniczna *'Problemy rozwoju badań naukowych w górnictwie naftowym i gazownictwie'*, IGNiG, Kraków.

Hewitt, B. and *Horn, J.*, 1994: Measurement of Leakage from Gas Distribution Systems & Strategy Development for Leakage Reduction. *International Workshop Environmental and Economic Impacts of Natural Gas Losses*, Prague, Czech Republic.

IPCC, 1993a: *Greenhouse Gas Inventory Workbook*, Volume 1. IPCC Draft Guidelines for National Greenhouse Gas Inventories.

IPCC, 1993b: *Greenhouse Gas Inventory Workbook*, Volume 2. IPCC Draft Guidelines for National Greenhouse Gas Inventories.

IPCC, 1993c: *Greenhouse Gas Inventory Reference Manual*, Volume 3. IPCC Draft Guidelines for National Greenhouse Gas Inventories.

Lott, R.A., 1994: Estimate of Methane Emissions from U. S. Natural Gas Operations. *International Workshop Environmental and Economic Impacts of Natural Gas Losses*, Prague, Czech Republic.

Meshkati, Sh.G. and *Groot J.M.*, 1994: A Study of Unaccounted-for Gas at the Southern California Gas Company. *International Workshop Environmental and Economic Impacts of Natural Gas Losses*, Prague, Czech Republic.

Petersen, L.B. and *Sorensen, A.K.*, 1994: Rehabilitation of Town Gas Networks and Use of No-dig Methods. *International Workshop Environmental and Economic Impacts of Natural Gas Losses*, Prague, Czech Republic.

Tokarzewski, J. and *Bednarski, R.*, 1995: Perspektywy rozwoju gazownictwa w Polsce. Konferencja naukowo-techniczna 'Perspektywy rozwoju gazownictwa w Polsce' SITPNiG, Kraków.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Estimating Emissions from Energy: Hungarian Experience

Sándor Molnár[1], **Tihamér Tajthy**[2], and **Tibor Takács**[1]

[1] *Systemexpert Consulting Ltd.,*
Mikoviny S. u. 2–4, 1037-Budapest, Hungary

[2] *Technical University of Budapest,*
Műegyetem rkp. 3, 1111-Budapest, Hungary

Abstract—Based on the historical features of the Hungarian energy system and on the fuel consumption, and taking into consideration the transition from a planned economy to a market economy, scenarios are elaborated which are selected as activity level for the determination of the energy-related GHG emissions in Hungary.

First, the whole Hungarian energy system is briefly outlined. The emissions of different greenhouse gases from fossil fuels are presented according to fuel types and to sectors. The different types of emissions have been calculated by using a detailed emission factor database, which has already been developed for Hungary. Finally, the average fuel related CO_2 emissions is presented for the period 1985–1987 calculated by the IPCC methodology. Using the so-called flexibility term (Article 4.6) of the Framework Convention on Climate Change (1992), Hungary has undertaken to stabilize the CO_2 emission on the average level of this period. In this calculation the recommended IPCC factors were used. Emissions have been determined both by the 'top-down' and the 'bottom-up' methods.

Our projections show that greenhouse gas emissions can be stabilized by the energy saving scenario, while the 'business-as-usual' scenario would lead to the increase of emissions.

Key-words: greenhouse gases; fuel related emissions, emission inventories, top-down estimations, bottom up estimations.

1. Introduction

For the determination of the historical and future greenhouse gas (GHG) emissions, the generally used emission factor method has been chosen. In the case of the energy related anthropogenic GHG emission, the fuel consumption are selected as activity level. The historical values of the fuel consumption might be collected from the regularly published energy statistical yearbooks, but the forecasting of the following fuel consumption in the transition period of the economy was not an easy task, because of the reconstruction of the old production system and of the overall economy, and the transformation from the planned economy to a modern market economy system.

In this transition period, there are significant changes and modifications everywhere. Thus the base scenario is not a continuous formation emerging from the past, not a really business as usual scenario, but a totally new formation. The other scenario investigated corresponds to the case of an extent and with significant financial support promoted energy saving and conservation, the main features and developments might remain nearly the same as in the base scenario regarding the transformation of the economy.

In the case of the non-energy related GHG emissions different adequate activity levels e.g., population, livestock, quantities of fertilizers and manure, etc., are to be selected for the calculation of the emissions.

The emission factors used for our investigation are either calculated or have been taken from the US-EPA AP-42, and from the IPCC and from the CITEPA Inventories (see *Tajthy*, 1993). If it was possible, in both cases they have been controlled by using measured data of the domestic emissions. Emission factors for CO_2 and CO have been determined by us, while those of NMVOC and CH_4 were taken from the above mentioned sources. Certain emission factors for NO_X have also been calculated for our own emission database.

Our emission factor database is a very detailed one. The calculations of the emissions are always carried out in the most detailed way; however, the final results are always aggregated.

In the following, the energy related GHG emissions are to be discussed in details. Because the selected activity level is the fuel consumption, at first the main characteristic features of the Hungarian Energy System (HES) are to be discussed, which affect evaluation of the HES. One of the most characteristic features of the HES is the lack of sufficient, clean and cheap domestic energy resources. Thus the energy demand of the country was satisfied by a great amount of imported energy. Our overall import dependence is in the range 50–60%, and our energy import dependence was based for a long time on one exporting country, which is not adequate from the point of view of the safety of the energy supply of the country, thus our strategic maneuverability was very limited.

Earlier, in the planned economy period, the energy prices were relatively low in Hungary. The energy prices have been dictated by the State Bureau of Prices and were nearly constant for a long period and have been independent from the variation of the world-market prices. Thus the producers had no interest in the energy saving, and did not intend on energy conservation or retrofitting of their old, aged production system or introducing low energy consuming technologies and appliances.

Due all of these, the overall energy use of the different sectors of the economy has been and to nowadays is very disadvantageous, compared to that of the member countries of the European Economic Community. But if we make a comparison based on the pro capita energy consumption, it is not higher than the European average. It reflects the low efficiency of the Hungarian economy and not of the Hungarian energy industry. The energy sector did its best for the reliable and effective, and low environmental polluting energy supply of the country within its possibilities. The structure of the fuel use was changed, new energy technologies and new types of energy have been introduced (e.g. desulfurization of the diesel oil and of the fuel oil, destructive technologies in the crude oil refinery, combined heat and electricity generation, combined cycle/gas turbines, fluidized bed combustion boilers for the electrical energy generation, electrofilter program in the coal-fired power plants, low-NO_x burners in power plants, intensive natural gas program, introducing nuclear energy for electrical energy production, introduction adequate tariff system to promote the structural change of the fuel use, etc.).

Regarding the fossil fuel fired in Hungary by sectors (*Fig. 1*) the greatest changes were caused by the introduction of the nuclear power plant for electrical energy generation and by the overall economic recession. Our 1840 MW nuclear power plant capacity produces about 45% of the domestic electrical energy with a capacity factor above 90%. In the last years the decrease in the electrical energy import was higher than the decrease of the domestic electrical energy consumption, thus we had to increase the domestic electrical energy production. Because our nuclear power plant operates with very high capacity factor we could increase the production of our fossil-fueled power plant only, thus their environmental pollution increased. In the fossil fuel consumption of the electrical energy production decreased and the nuclear fuel has increased.

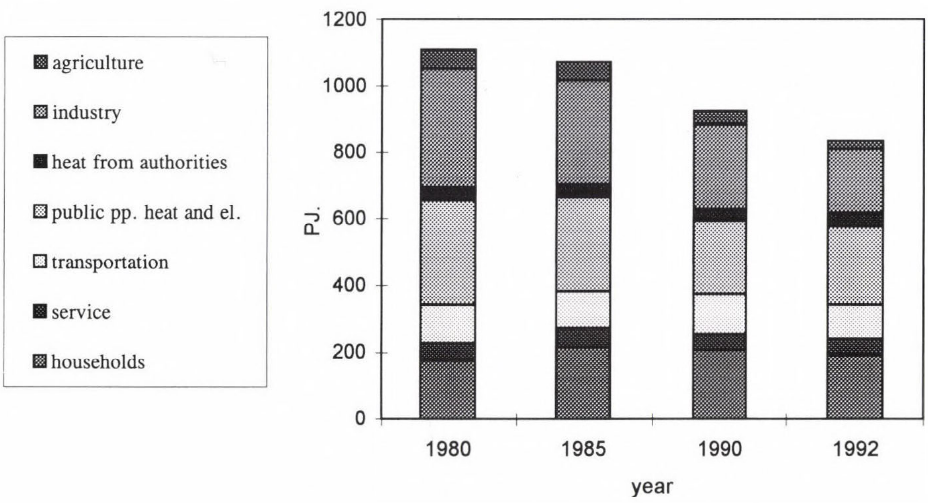


Fig. 1. Fossil fuel consumptions in Hungary by sectors.

2. Fuel Related Emissions and Projections

In this paper the energy-related emissions both of the direct GHGs (CO_2, CH_4, N_2O) and of the indirect GHGs (CO, NO_x, NMVOC) are presented.

In *Figs. 2–3*, the emissions of CO_2, are shown by sectors and by fuel types. The carbon dioxide emissions decreased from 92 million tons in the year 1980 to 66 million tons in the year 1992. The most significant decrease occurred in the emissions of the public power plants, because of the operation of our nuclear power plant, and of the industrial sectors, because of the economic recession and of the natural gas program. The drastic decrease occurred in the CO_2 emissions associated with solid fuel use.

In *Figs. 4–5*, the methane emissions are shown by sectors and by fuel types. Most of the methane emissions is produced by the fuel use of the households and of the industry, and the most important source of the methane emissions is the solid fuel use.

The significant decrease of the methane emission is mainly caused by the decrease of the coal consumption of the households and of the industry. The methane emissions decreased from 23 kt in the year 1980 to 12 kt in the year 1992.

In *Figs. 6–7*, the N_2O emissions are shown by sectors and by fuel types. The greatest polluters are the households, the power plants and the industrial sectors, and the sources of the N_2O emissions are the uses of the solid and liquid fuels. The N_2O emissions decreased in the period 1980–1992 from 9.5 kt to about 6 kt.

The NO_x emissions (*Fig. 8*) decreased from 250 kt to 173 kt in the period 1980–1992. About half of the NO_x pollution is emitted by the transportation sector, and mainly from the liquid fuels, because of the aged and high specific consumption car fleet in Hungary. There is a slight decrease in the NO_x emission caused by the power plants as an outcome of the retrofitting of the old gas — and coal fired boilers, of the introduction of low — NO_x burners and of the hybrid fluidized bed combustion boilers and of the market penetration of the nuclear electricity and of the combined cycle gas turbines. In the following years, the emissions caused by the transportation will remain dominant. According to the expectations, the aging of the car fleet will be compensated to some extent by new, modern cars, but especially in rural areas the old, high consuming and aged car fleet may remain dominant in the next follow years.

The carbon monoxide emissions (*Fig. 9*) decreased in the period 1980–1992 from about 760 kt to about 590 kt. Here, as in the case of the NO_x emissions, the emissions of the transportation sector are the most important. About 85 % of the CO emissions is caused by the old and high specific fuel consuming car fleet. The amount of the CO emissions caused by the transportation did not change significantly in the last years. The slight decrease is mainly caused by the reduction of the liquid fuel use because of the price increase of the motor fuels.

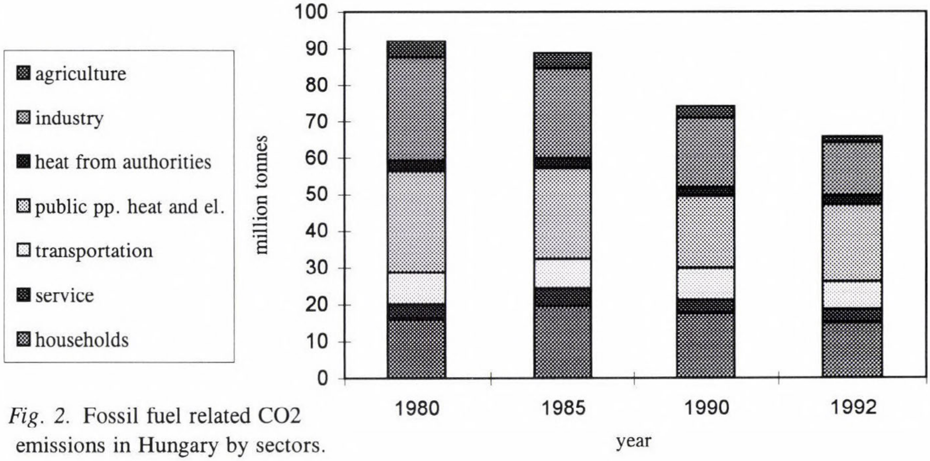


Fig. 2. Fossil fuel related CO2 emissions in Hungary by sectors.

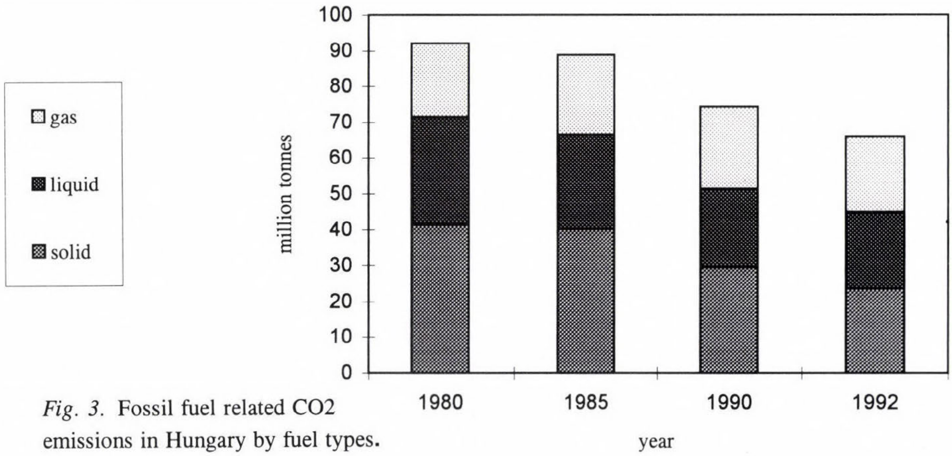


Fig. 3. Fossil fuel related CO2 emissions in Hungary by fuel types.

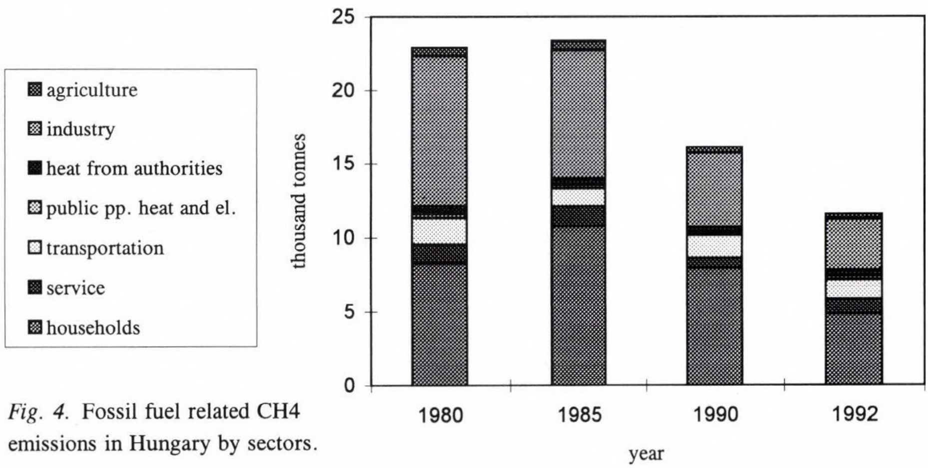


Fig. 4. Fossil fuel related CH4 emissions in Hungary by sectors.

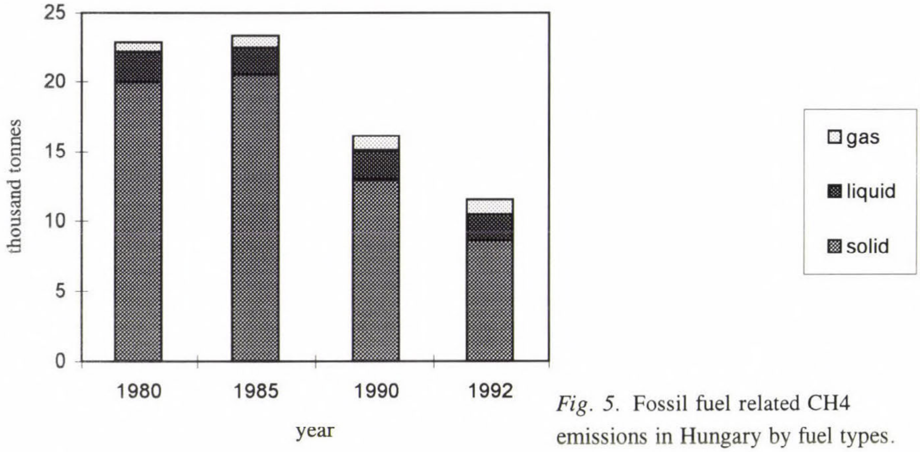


Fig. 5. Fossil fuel related CH4 emissions in Hungary by fuel types.

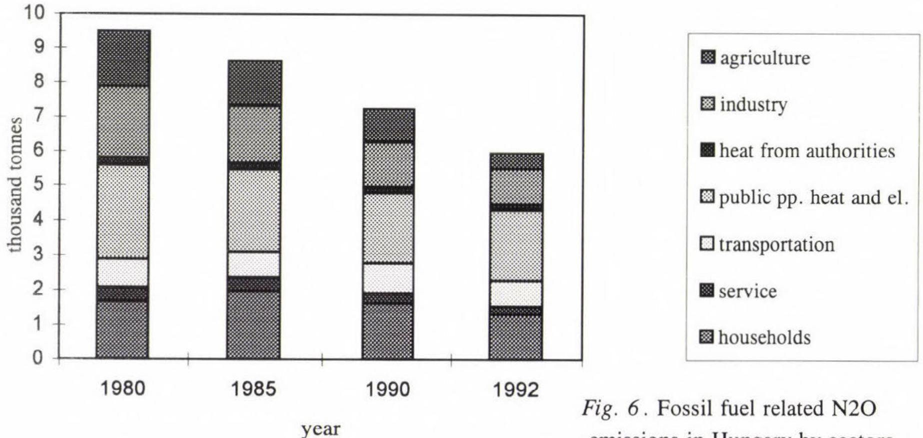


Fig. 6. Fossil fuel related N2O emissions in Hungary by sectors.

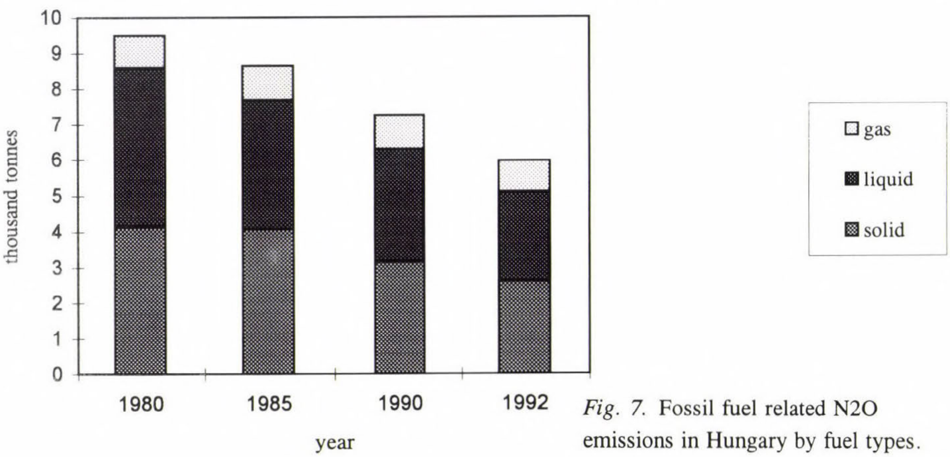


Fig. 7. Fossil fuel related N2O emissions in Hungary by fuel types.

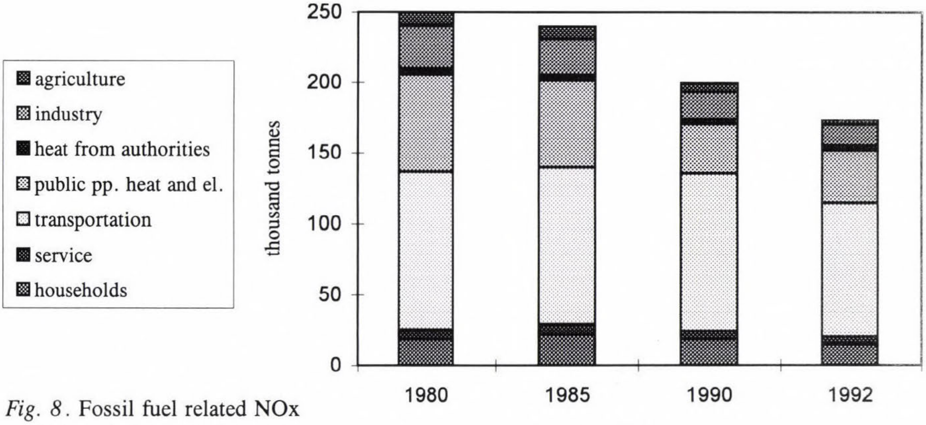


Fig. 8. Fossil fuel related NOx emissions in Hungary by sectors.

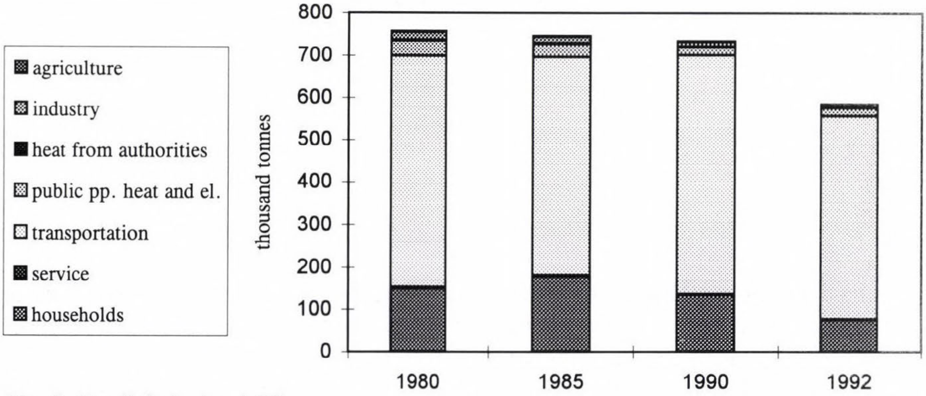


Fig. 9. Fossil fuel related CO emissions in Hungary by sectors.

Regarding the non-methane volatile compound (NMVOC) emissions (*Fig. 10*), significant decrease occurred behind the year 1985 in the emissions caused by the households and by the industry. The emissions decreased in the period 1980–1992 from about 103 kt to about 58 kt. The solid fuel use, especially the fuel wood fired by the households, is the deterministic in the NMVOC emissions.

For comparison, in the following tables the energy-related and non energy-related CO_2 and methane emissions are shown. While the non energy-related CO_2 emissions are about one-third of the energy-related emissions, as far as that of the methane emissions are much higher than the energy-related methane emissions. Among the non energy-related methane emissions, the emissions caused by domestic wastes and domesticated animals are mainly deterministic, the undomesticated animals and the coal mining have minor effects. The above projections are based partly on well known energy environmental models. These models have been adapted and tested for the Hungarian electricity sector (see *Systemexpert,* 1995a and 1995b).

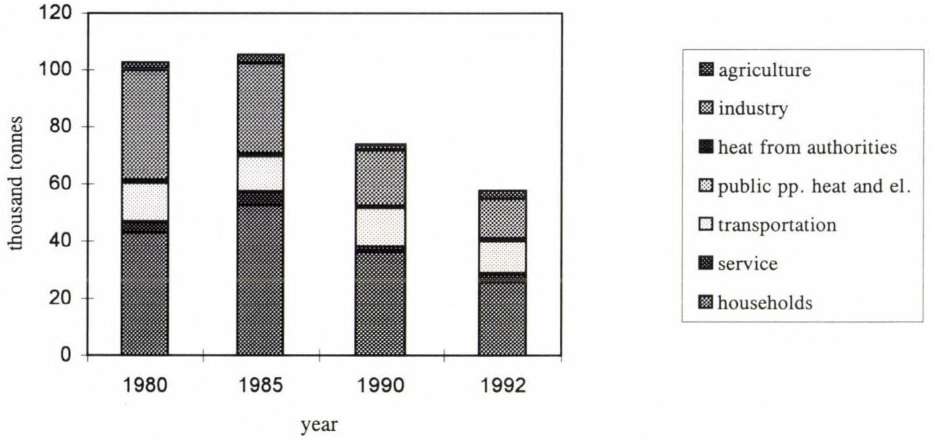


Fig. 10. Fossil fuel related NMVOC emissions in Hungary by sectors.

3. *CO_2 Emissions Calculated by the IPCC Methodology*

The Parliament of Hungary ratified the Framework Convention on Climate Change in December, 1993. Using the so-called flexibility term (Article 4.6) of the convention Hungary has undertaken to stabilize CO_2 emission on the average level of the period 1985–1987 instead of selecting 1990 as a base year. In this section, we present the results of the 'top-down' and the 'bottom-up' estimations for CO_2 emissions according to the IPCC methodology. These calculations were based on the emission factors recommended by the IPCC guidelines. Results of the non-IPCC methodology are presented by *Tables 1, 2* and results of the IPCC methodology are shown by *Tables 3* and *4.*

4. *Conclusion*

Results of the calculations based on the IPCC methodology roughly coincide with the results based partly on the developed Hungarian emission factor database. Recent investigations show that GHG emissions can be stabilized by the energy saving scenario, while the 'business-as-usual' scenario would lead to the increase of emissions.

Table 1. Energy related and non-energy related CO_2 emissions in Hungary in thousand tons (Gg)

	1980	1985	1990	1992	1995	2000
Non-energy related:						
Breathing of population	9420	9290	9110	9079	9050	8910
Domestic waste	524	517	507	504	503	496
Domesticated animals	13730	13020	11800	8530	8150	10250
Undomesticated animals	260	299	311	313	322	323
Cement production	6030	5100	4860	2750	3050	4000
Total	**29964**	**28226**	**26588**	**21176**	**21075**	**23979**
Energy-related:	**92050**	**88830**	**74200**	**65930**	**65875**	**73451**

Table 2. Energy related and non-energy related CH_4 emissions in Hungary in thousand tons (Gg)

	1980	1985	1990	1992	1995	2000
Non-energy related:						
Manure of popul.	0.75	0.74	0.72	0.72	0.72	0.71
Domestic Waste	232.71	229.56	225.12	224.12	223.49	220.21
From the soils	1.62	1.62	1.62	1.62	1.62	1.62
Rice cultivation	6.49	6.49	6.49	6.49	6.49	6.49
Thermal waters	20.23	20.23	20.23	20.23	20.23	20.23
Domesticated aimals	149.04	135.43	119.28	91.48	84.48	105.86
Undomesticated animals	56.49	53.38	48.02	35.15	33.14	41.88
Coal mining	56.80	49.10	36.40	23.80	22.90	13.00
Total	**524.13**	**496.55**	**457.88**	**403.61**	**393.07**	**410.00**
Energy-related:	**22.87**	**23.37**	**16.13**	**11.53**	**12.06**	**12.87**

Table 3. Top-down estimation for energy related CO_2 emissions

Fuel type	CO_2 emissions (Gg-year) 1985–1987
Natural gas (dry)	20552
Liquid fuel (total)	25054
Solid fuel (total)	34483
Total	**80089**

Table 4. Bottom-up estimation for energy related CO_2 emissions

Sector	CO_2 emissions (Gg-year) 1985-1987
Transformation	36910
Industry	10883
Transport	7731
Commercial/Trade	3403
Residential	16629
Agriculture/Forestry	3233
Other emissions	1300
Total	**80089**

References

Systemexpert, 1995a: *Analysis of the Newest Energy Strategy of the Hungarian Power Companies by the Model EFOM_ENV* (in Hungarian). Research Report. Systemexpert Consulting Ltd, Budapest, Hungary.

Systemexpert, 1995b: *Environmental Evaluation of Energy Strategies of the Hungarian Power Companies by the Model BALANCE-IMPACTS* (in Hungarian). Research Report, Systemexpert Consulting Ltd, Budapest, Hungary.

Tajthy, T., 1993: Emission of the air pollutants from the fuel consumption (in Hungarian). *Magyar Energetika I. 3*, 38-43.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Estimating Emissions in a Time of Structural Change: Czech Republic Experience

Miloš Tichý

SEVEN, The Energy Efficiency Center,
Slezská 7, 120 56 Prague 2, Czech Republic

Abstract—Under the framework of the US Country Studies Program, an inventory of greenhouse gas (GHG) emissions for 1990 was conducted. The following seven GHGs were taken into account: CO_2, N_2O, CH_4, NO_X, CO, NMVOC, and halocarbons (CFCs and HCFs). The sources of GHGs were grouped according to the Intergovernmental Panel on Climate Change (IPCC) methodology. For emission calculations, locally developed emission coefficients were used whenever they were available. IPCC-recommended and CORINAIR coefficients were used where no local information was available. The total emissions of GHG covered by the Framework Convention on Climate Change (FCCC) were 181 million tons of CO_2 equivalent. Moreover, 30 million tons of CO_2 equivalent of halocarbons (CFCs and HCFs) were emitted. The most important GHG is CO_2 (89 percent). Comparison with CORINAIR methodology was performed. From the knowledge gained during this work, the concept of 'in depth' and 'routine' inventories is proposed.

1. Introduction

This paper summarizes the inventory of GHG emissions in the Czech Republic that was conducted in the framework of the US Country Studies Program.

The inventory contains primarily gases that directly cause the greenhouse effect, that is, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons (CFCs and HCFCs), but also gases with an indirect effect, the precursors to ozone creation, that is, carbon monoxide (CO) and nitrogen oxides (NO_x). Upon the recommendation of the Intergovernmental Negotiation Committee (INC), the year 1990 was selected for the inventory.

The purpose of this paper is to give an overview of the methods and results of the inventory together with some ideas that emerged from the inventory process. The detailed report on the inventory has been published separately (*Tichý et al.*, 1995).

2. Methods and Data Sources

The Czech Republic maintains an air pollutant emissions, technology oriented database, REZZO (for a short description see (*Tichý et al.,* 1995), REZZO is concentrated on local pollutants (SO_x, NO_x, and so forth) but it contains information on spent fuel. We used these data for averaging emission coefficients; this is important especially for gases other than CO_2. Several years ago the CORINAIR Inventory System was applied, and data for 1990 was published recently (*Krátká et al.,* 1994). But both CORINAIR and REZZO served as a source of supplementary data for this inventory, which was performed using the IPCC/OECD methodology.

The IPCC methodology is described in three documents (*IPCC,* 1994) and implemented by the MINERGG Program. To enable the future international comparison of results, we used the following classification of sources given in this methodology:

- The energy sector (combustion and fugitive processes),
- Industrial processes,
- Agriculture,
- Managed forest,
- Waste.

In accordance with the IPCC methodology (*IPCC,* 1994), inventory results are presented in *Tichý et al.* (1995) in the form of standard minimal tables. In these tables, the emissions and data that characterize an activity (for example, the amount of fuel burned) were independently set and their ratio is the aggregated emissions factor. In this inventory, emissions coefficients and activity-characterizing data were more or less independently established. Their mathematical product is emissions. Aggregated emissions factors, that is, mean values for categories or subcategories, are given only when they have some significance. This deviation from the standard can be misleading, but given the clear relationship of all three variables, the presented tables can be used as IPCC standard tables.

Combustion processes have a specific importance in the inventory because they are the main source of GHGs, and CO_2 is the most important GHG. Therefore, the inventory of CO_2 emissions from the energy sector was performed by the following two techniques:

- IPCC/OECD methodology as described in *IPCC* (1995). The method is oriented to the entrance point of the energy sector source side, that is, primary resources. There are two main objections to this simple and fast method:
  - Activity data can sometimes be misleading because fossil fuels are not traced to their end (burning).

- Emission factors do not respect the technology used to burn fuels. This not important in the case of CO_2, but it is critical for NO_x and some other gases.

- Emissions source oriented method. To avoid these inadequacies we developed a method of tracing gases to their burning point. The main source of activity data are inputs to the transformations and final energy consumption parts of the energy balance (*Federal...*, 1991b). In parallel, a weighting method was developed to get aggregated emission factors for all GHGs (*Tichý et al.*, 1995).

Total CO_2 emissions gained by the two methods are in a surprisingly good agreement (2 percent), but emissions from gaseous fuels differ by 45 percent. We have modified the IPCC methodology in two other sectors:

- Emissions of methane from waste are the third important source (after combustion and agriculture). We have used local measurements of chemical kinetics to estimate emissions. The obtained result is 20 percent lower than the one obtained by the reference process.
- CO_2 emissions and sinks from managed forests were also estimated, and the total absorption is more than three times greater than the result of the IPCC reference method.

Halocarbons (CFCs and HCFCs) have a special position among GHGs. The inventory of their emissions was conducted by audit, that is, by individual survey at its sources.

The emissions coefficients recommended in the IPCC/OECD methodology were used in cases when proven coefficients specific for local conditions were unavailable. CORINAIR coefficients were used for some source groups.

The MINERGG program was not used for the emissions calculations themselves, because it does not allow a fine enough categorization of sources, especially in the energy sector. Instead, a standard spreadsheet program was used for inventory calculations.

The main data sources for activity data were the *Federal...* (1991a) and, especially, *Federal...* (1991b). Those data were published for many years for both the Czech and Slovak Republics and federated Czechoslovakia. Therefore the separation into two countries caused no serious problems. Problems appeared only in the case of the CFCs and HCFCs inventory, which was performed by auditing all enterprises involved in CFCs and HCFCs.

3. *Results*

Total emissions are summarized in *Table 1*. Emissions of GHGs covered by the FCCC were 181 million tons of CO_2 equivalent. Moreover, 30 million tons of CO_2 equivalent of halocarbons (CFCs and HCFCs) were emitted. The most important GHG is CO_2 (90 percent), and combustion processes are the most important source (96 percent) of CO_2 emissions. More than half of CO_2 is emitted from processes of energy production and transformation (59 percent). Most emitted methane was released from hard coal mines (56 percent). The total emission of CO_2 was 164 million tons, that is, 15.8 t_{CO2}/inhabitant and 0.2 $kg_{CO2}/CZK^1{}_{GDP}$ (in 1991 prices).

Table 1. Summary of GHG emissions

Gas	CO_2	CH_4	N_2O	NO_x	CO	NMVOC	CFC+HCFC	Total
Emission (MT)	164	0.9	0.03	0.9	0.7	0.3	0.05	
Emission (MT_{CO2} equivalent)	164	10	7				30	211
Relative emissions without CFC+HCFC	90%	6%	4%					
Relative emission including CFC+HCFC	77%	5%	3%				14%	
GWP	1	11	270				see *Tichy et al.* (1995)	

The first attempt at a comparable inventory was published in *Maldan et al.*, (1993). The only other inventory of comparable breadth is the CORINAIR 90 (*Krátká et al.*, 1994a), which was developed by the authors of the primary input report for this study (*Krátká et al.*, 1994b). The CORINAIR final report, published at almost the same time as this study was being completed, unfortunately does not contain very many detailed numbers; it does not contain any data on activities and very few emissions coefficients. Thus the concluding comparison that follows limits itself mostly to merely noting the differences without apparent reasons.

Carbon Dioxide: The largest source of this most important contributor of the greenhouse gases is combustion processes, which account for approximately 96 percent. The second largest source is cement production at 2.5 percent. The only sink—forests—seems to be almost negligible in the total balance (2.3 million tons, that is, about 1.2 percent). Distribution of CO_2 emissions from combustion among sectors is given in *Fig. 1*. The large portion of emissions from the energy sector (almost 60 percent), and the relatively small share from transportation are remarkable. The only sources of CO_2 that were not included in this graph are cement production and metallurgy.

[1] The estimate of contribution to the greenhouse effect for different gases was calculated using corresponding values of the global warming potential (GWP); The current exchange rate is about 26 CZK/USD.

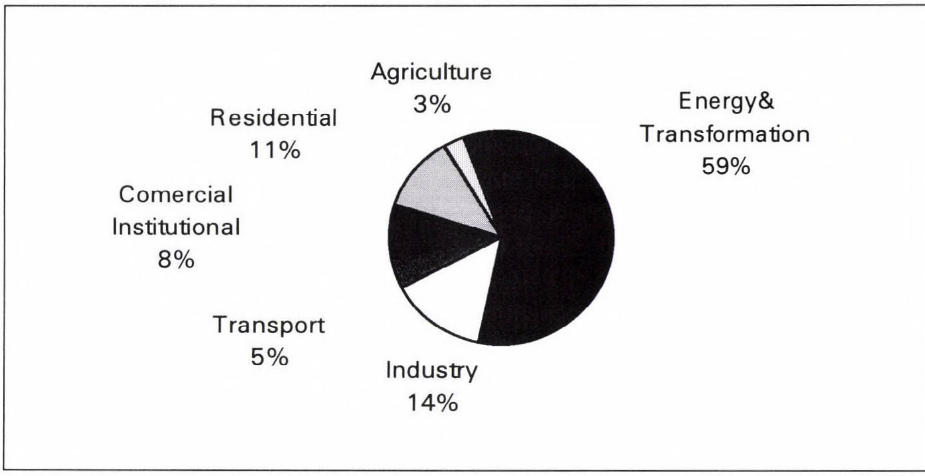


Fig. 1. CO_2 emissions from combustion.

Emissions of 164 million tons are 3 percent higher than the results of the preliminary inventory published a year ago (*Moldar et al.,* 1993). The difference is negligible, given that the uncertainty of emissions is estimated at 5–15 percent. The difference of 9 percent with the CORINAIR inventory (*Tichý et al.,* 1995; *Krátká et al.,* 1994) is caused primarily by substantial differences for emissions from industrial processes (cement production) and waste. Emissions from combustion processes are surprisingly close (4 percent), given the difference in fuel consumption (activity data for CORINAIR is taken from the REZZO Database (*Tichy et al.,* 1995)).

Methane: The most significant source is the energy sector, with a dominant share of emissions resulting from coal mining (51 percent of total emitted methane). Distribution of methane emissions among sectors is presented in *Fig. 2.*

Emissions of 941 million tons are less than half of the preliminary estimate in *Moldan et al.* (1993). The differences are mainly in the estimate of emissions from the distribution and processing of natural gas and crude oil. *Moldan et al.* (1993) gives an estimate that is almost twentyfold, coal mining and agriculture (for both it gives an estimate that is almost double). The emissions estimate published here is about two-thirds that published in the CORINAIR inventory. The difference in the emissions estimate from coal mining, resulting from differences in emissions factors, is important.

Nitrogen oxides and carbon monoxide are less significant greenhouse gases. Again, their major source is the energy sector because of the large amount of burned fuels. Differences from the CORINAIR inventory are caused by a large variation in emissions factor values from various sources, especially for nitrogen oxides.

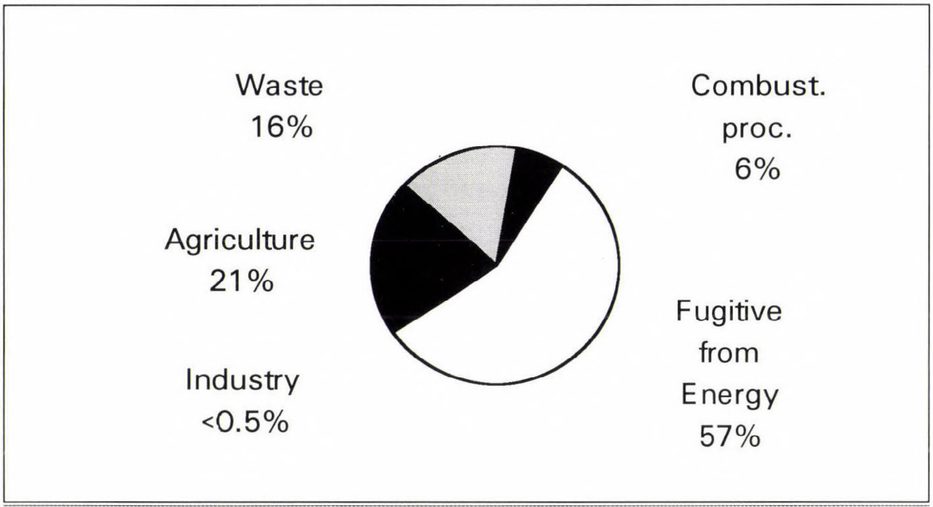


Fig. 2. Methane emissions.

The greatest source of *non-methane fugitive substances* is fumes from the use of solvents for paints and finishes and chemical cleaning processes. The results are preliminary and highly uncertain because this group has been monitored for the shortest period of all monitored gases. Moreover, production data is often marked as confidential business information and thus difficult to obtain.

Halocarbons (CFCs and HCFCs) form the second most significant group of gases, after CO_2. Their significant share (14.3 percent in 1990), however, has markedly declined since 1990 as a result of measures evoked by the Montreal Protocol.

4. Conclusion

An emissions inventory of seven GHGs was performed for the Czech Republic for the year 1990. Most attention was paid to CO_2 and the energy sector because they are the most important GHG and the main source. There are still some open questions in the inventory (for example,. emissions from solvents) but the prevailing part of emissions was estimated with reasonable uncertainty, and differences from comparable inventories are acceptable. Reducing the uncertainties can be achieved by increasing the statistical data reliability and by further reevaluating the default emissions factors for domestic purposes, mainly for GHGs or precursors other than CO_2.

The concept of in depth and routine inventories emerged from the knowledge gained during this work. An in depth inventory like the one presented provides a base for several years. A routine inventory (employing activity data published for only one year) is enough to have a clear picture each year.

Whereas knowledge of sources and emission factors is steadily growing, a substantial effort should be devoted to uncertainty considerations, keeping in mind that data from economic statistics are not 'statistical' data from the mathematical point of view, with implications for the Gaussian uncertainty distribution. The IPCC table (*IPCC,* 1994) assessing this problem is a subjective attempt.

A considerable effort on an international scale should be devoted to combining the IPCC and CORINAIR inventory systems.

References

Federal Statistical Office, 1991a: *Statistical Yearbook of the ÈSFR 1991*. Federal Statistical Office, Prague.

Federal Statistical Office, 1991b: *Energy Balance of the Czech Republic for 1990*. Federal Statistical Office, Prague.

IPCC/OECD, 1994: *Draft Guidelines for National Greenhouse Gas Inventories*. Vol. 3.

Krátká, H., et al., 1994a: *CORINAIR 90, Emissions Inventory for the Czech Republic*. Czech Hydrometeorological Institute, Prague.

Krátká, H., et al., 1994b: *An Inventory of Greenhouse Gas Emissions in the CR in 1990*. Czech Hydrometeorological Institute, Prague.

*Moldan, B., et al.,*1993: *The Strategy of Reducing the Risk of Climate Changes*. National Climate Program, Prague.

Tichý, M., Voráčková, Z., and *Dvorák, P.*, 1995: *Greenhouse Gas Emissions Inventory, Czech Republic 1990.* SEVEn 94/013/a,c, Prague.

PART III

Mitigating the Climate Change: Examples of Response Policy

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Key Issues in Estimating Greenhouse Gas Emissions from a Joint Implementation Project in the Energy Sector

Suzanne Billharz

Center for Clean Air Policy,
Jana Masaryka 1, 120 00 Prague 2, Czech Republic

Abstract—Greenhouse gas emissions must be estimated for individual joint implementation[1] (JI) projects in addition to national inventories. Special issues arise in the context of joint implementation, which raise methodological questions. This paper summarizes the greenhouse gas estimates calculated for a specific JI project in the energy sector in North Bohemia and reviews some key issues involved.

The estimates for this JI project are first put into the context of the national inventories, international and national reporting requirements, and the role of the Center for Clean Air Policy (CCAP). Greenhouse gas sources and sinks of a fuel-switching project at a district heating plant are summarized, and estimates of the project baseline and CO_2 emissions reductions resulting from the project are presented. The underlying assumptions, uncertainties affecting emissions, future potential factors, secondary effects, and additional issues are identified and discussed, sketching a sample picture of the range of technical and political considerations that must be taken into account. Finally, specific points to consider, particularly regarding baselines, are summarized.

Key-words: joint implementation, cogeneration, baseline, emission reductions.

1. Context

1.1 National Inventories and Joint Implementation

Estimating greenhouse gases for both national inventories and joint implementation (JI) projects are part of the same larger process of working toward a common goal, that of the Framework Convention on Climate Change (FCCC): 'stabilization of greenhouse gas concentrations in the atmosphere at a level that

[1] Joint implementation is a mechanism used in international treaties through which two or more parties to an international agreement may undertake activities together in order to implement the agreement.

would prevent dangerous anthropogenic interference with the climate system'[2]. Inventories provide the indispensible basis for formulating policy, tracking progress over time, and checking national policy performance. It is clear, however, that further GHG reductions are needed in addition to those brought about by governmental measures if global emissions are to be stabilized. This was confirmed at the Conference of the Parties in Berlin in March 1995, at which there was general agreement that current commitments are inadequate to reach the goal of the Convention.

Thus, the Conference of the Parties established a pilot program for Joint Implementation.[3] JI projects can provide a successful mechanism to tap private sector resources and minimize costs in order to bring about reductions in GHG emissions. There is potential for GHG reductions through JI, particularly in the Central and Eastern European region in the energy sector. The Decin project is a model that could serve as a precedent and catalyze development of other similar projects in the region.

1.2 Reporting Convention for GHG Emission Reductions from JI

National programs

Under national JI programs such as the U.S. Initiative on Joint Implementation (USIJI), reductions resulting from JI projects are required to be reported, of course, as the basis for claiming CO_2 credits. In order to be accepted to the program, the application to the USIJI must include estimates of greenhouse gas emissions and reductions. At a later stage, after the results from implementation of the project have been monitored and verified, the partners may claim the actual amount of greenhouse gas reductions achieved.

The Decin project was approved February 3, 1995, by the USIJI panel and is thus chosen as one of seven projects to be included in the U.S. pilot program. These seven projects represent private investments of approximately $40 million.

The Czech Republic is developing its own pilot JI program and plans to establish an interministerial JI project review panel in the near future.

International reporting

Under the FCCC, Annex 1 countries are required to report their greenhouse gas emission inventories periodically, although reporting on emission reductions from JI is not required. Countries undertaking JI projects are nevertheless

---

[2] Article 2, United Nations Framework Convention on Climate Change

[3] FCCC/CP/1995/L.13

encouraged to report on them in national communication in order to facilitate the exchange of information during the early pilot phase and to promote international consultation of early experiences with JI.

1.3 The Role of the Center for Clean Air Policy

The Center for Clean Air Policy (CCAP) is a nongovernmental nonprofit organization established in 1985 by nine U.S. governors. A major focus of CCAP is to develop innovative policy approaches to major environmental and energy issues utilizing market-based solutions. In the context of climate policy and joint implementation (JI), CCAP has brokered a first-of-its-kind JI project to decrease greenhouse gas emissions and demonstrate the use of private sector financing to reduce greenhouse gases. The project, at the Bynov district heating plant in the city of Decin, North Bohemia, involves switching the fuel of the heavily polluting plant from brown coal to natural gas, installing gas engines for cogeneration, and improving the efficiency of the heat distribution network. This paper focuses on the GHG emission calculations for the Decin project.

2. The Project

2.1 Key Components

The project involves three major changes that affect the level of greenhouse gas emissions from the site: switching the fuel of a district heating plant from lignite coal to natural gas, installing the capacity for cogeneration, and installing an insulated heat distribution network.

The fuel switch involves replacing the existing coal-fired boilers with natural gas-fired internal combustion engines and associated exhaust-gas/hot-water heat exchange equipment. The gas engines will have a capacity of 10.6 MW and a 90 percent combustion efficiency. (This replaces the current 19.6 MW coal boilers which have a combustion efficiency of only 63 percent.) The engines will produce hot water to provide both heat and potable hot water to the apartment blocks. The new plant will be connected to a natural gas pipeline from Russia.

Through cogeneration, the gas engines will produce electricity in addition to heat, and this electricity will be sold to a regional electricity distribution enterprise. An agreement for the sale of the electricity has already been negotiated. The City of Decin will recieve 1.67 Czech crowns per kWh (approximately 6 cents per kWh) during peak hours and 0.70 Czech crowns per kWh (approximately 2.6 cents per kWh) during off peak hours.

The efficiency of the hot-water distribution network will also be improved. Presently, the distribution network delivers heat in the form of steam to the apartment blocks. The steam must then be converted to hot water. Instead, the Bynov plant will deliver hot water directly, eliminating the need to convert steam to hot water. Thus, the existing heat exchanger stations will be replaced by individual compact heat exchanger stations. Insulated pipes will also be installed in the heat delivery system to minimize system losses. The City of Decin is, moreover, planning to install meters at each apartment building to measure delivery of heat and hot water. In the long run, the City is planning to install individual thermostats in each apartment to more efficiently regulate the delivery of these services.

With these new measures, the Bynov plant will reduce its energy consumption initially from 170,700 GJ to 117,000 GJ while continuing to provide 107,000 GJ of heat production throughout the life of the project. Through the energy efficiency improvements and switch to natural gas, the CO_2 emissions at the Bynov plant will be reduced overall by 5,992 metric tons (see *Table 1*).

2.2 Greenhouse Gas Sources and Sinks

Sources at the Facility:

Carbon Dioxide (CO_2)

The Bynov plant currently burns local brown coal with a carbon content of 41.8 percent and emits 19,582 metric tons of CO_2. The projected emissions reductions resulting from the simple fuel switch are calculated at 11,653 metric tons—a 60 percent reduction from the 1991 level. The City decided later to go forward with the cogeneration project, and the CO_2 emissions were then estimated (based on 1993 data) slightly higher at 13,590 metric tons.

Sources Affected by the Project:

Methane (CH_4)

As a result of the pipeline, there will be some leakage in the transportation of natural gas. Because the portion extending from Usti and Labem is newly constructed, no pipeline leakage is expected in the near future. The parent pipeline serves the German market from Russia and the existing leakage rate is unknown. A joint implementation project between Ruhr Gas and the Russian government is planned, however, which will reduce overall leakage from the pipeline, and thus decrease overall methane emissions.

As the amount of coal that is burned is reduced, coalbed methane emissions will also be reduced. This will not be a significant amount, however, because the coal comes from a non-gaseous mine.

Table 1. Characteristics of the Bynov Project

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	OLD					NEW						CO2		
Year	Heat Demand	Electricit Product.	Coal Consumpt	CO2 emiss.	Alt. CO2 emiss. fr.	Heat Demand	Electricity Product.	Gas Consum.	CO2 emiss	Cogen Savings		Due to Fuel	Due to	
	TJ	MWh	tons	tons	hard coal	TJ	MWh	mil. cu.	tons	fr. coal	fr. system	Switch	Cogen	Total
										tons	tons	tons	tons	tons
1996	107	0	12800	19582	19356	107	26152	248	13590	32167	20660	5992	20660	26652
1997	105	0	12535	19177	18955	105	25775	242	13309	31703	20362	5868	20362	26230
1998	103	0	12273	18776	18558	103	25381	237	13031	31219	20051	5745	20051	25796
1999	101	0	12007	18369	18156	101	24975	232	12748	30719	19730	5621	19730	25351
2000	98	0	11742	17964	17756	98	24560	227	12467	30209	19402	5497	19402	24899
2001	96	0	11478	17560	17357	96	24137	222	12187	29689	19068	5373	19068	24442
2002	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2003	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2004	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2005	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2006	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2007	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2008	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2009	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2010	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2011	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2012	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2013	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2014	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2015	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2016	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2017	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2018	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2019	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978
2020	94	0	11213	17155	16957	94	23707	217	11906	29160	18729	5249	18729	23978

Nitrogen Oxide (NO_x)

The demand for heat and energy input will decrease as a result of introducing various energy efficiency improvements in apartment blocks, individual flats, and the heat distribution network. NO_x emissions will be reduced further because of the installation of gas engines and a more energy-efficient peaking boiler that also uses low NO_x burners. Furthermore, natural gas does not have fuel-bound NO_x as coal does.

Ozone (O_3)

Reductions in NO_x will also reduce local ozone levels, thereby reducing an additional greenhouse gas.

3. The Estimates

3.1 Estimate of Greenhouse Gas Emissions

A. *Without* the project (baseline)

The existing Bynov district heating plant has a 19.6 MW capacity and burns 12,800 tons of lignite coal annually. With an annual heat production of 107,000 GJ and an annual heat combustion (input) of 170,000 GJ, the combustion efficiency at the facility is approximately 63 percent. The average carbon content for lignite coal burned in North Bohemia is 41.8 percent carbon. Using this percentage, CO_2 emissions were calculated using the following equation:

$$\text{(tons coal) (41.8 percent carbon) (3.667 } CO_2 \text{ conversion factor)} = \text{tons } CO_2 \text{ emitted.}$$

Based on this information, baseline CO_2 emissions are calculated at 19,582 metric tons.

Emissions in the year 2000 are expected to drop to 17,964 tons, based on a projected lowering of the heat demand from 107,000 GJ in 1996 to 98,000 GJ in 2000 (see *Assumptions*, below). Existing laws such as the Clean Air Act, also have important impacts on the baseline, as existing plants must comply with emission limits for nongreenhouse gases that also affect the emissions of greenhouse gases, although greenhouse gases are not themselves regulated. CO_2 emissions are expected to stay the same or rise depending on the compliance strategy for SO_2 chosen at the Bynov plant.[4]

If meeting air quality standards were the only goal of the project, use of Russian natural gas would not be a cost-effective option. CO_2 emissions would not be a consideration for the City in the absence of the JI opportunity.

B. Estimate of greenhouse gases *with* the project (reductions)

When the Bynov plant switches from lignite coal to natural gas, the capacity will be reduced from 19.6 to 10.6 MW and efficiency will increase from 63 percent to approximately 91 percent. The increase in efficiency results from two main changes:

- Increased combustion efficiency of the gas engines as compared to the coal-fired boilers
- System conversion from steam-based heat to hot water-based heat, and efficiency improvements in the distribution network.

In addition, under federal law thermostats and energy efficiency improvements in apartment buildings and individual flats are due to be installed over the next three years, further decreasing demand on the system.

Based on the estimates given in the feasibility study, the new cogeneration facility will consume 7 million m^3 of natural gas during the first year of the project (1996). An annual percentage change for the projected heat demand was calculated through 2020, and from this the annual change in fuel consumption — assuming fuel consumption will change relative to heat demand — for the life of the project. Applying the average carbon content of natural gas (according to the U.S. Congressional Office of Technology Assessment), the CO_2 emissions were calculated as follows:

$$(\text{m}^3 \text{ natural gas})\ (3.3 \text{ lbs. carbon/hundred cubic feet})$$
$$(3.667\ CO_2 \text{ emission factor})\ (2{,}200 \text{ lbs/metric ton}) = \text{tons } CO_2.$$

Please refer to the emissions estimate as shown in Table 1.

---

[4] To comply with the Czech Clean Air Act, district heating facilities are choosing one of three methods:

(a) Switching from local high sulfur coal to low-sulfur lignite coal. Much of this low-sulfur coal is imported from Poland. While this will reduce SO_2 emissions, it will not affect CO_2 emissions.

(b) Switching to town gas (coal gasification); however, town gas is being phased out.

(c) Desulfurization through use of scrubbers and development of clean coal technologies. This is expensive and it solves only one problem (SO_2) without addressing other problems, such as ash disposal and dust and land degradation from coal mining.

Because the City of Decin has chosen one of the most expensive cogeneration options and the fuel is more expensive, the project only becomes viable under a JI scenario. Demonstrating a gas-fired district heating cogeneration facility will provide an example of one way to meet both environmental and long-term economic needs of local communities in the country.

Assumptions:

- Consumer heat demand will not change due to the plant burning natural gas instead of coal.
- Over the next five years, heat demand is expected to go down by 20 percent because of existing regulations mandating the installation of thermostats and other energy-efficiency improvements. However, during these same five years, it is expected that new one- and two-family houses with a total heat demand of 8,000 GJ (7 percent) will be connected to the system. Table 1 combines these effects on demand through the year 2001 at Bynov. After the year 2001, the heat demand is expected to remain steady.
- The emission reductions are outlined in Table 1; note that the U.S. utilities are registering only a portion of the reductions that will be achieved by the Bynov project and they are not registering the emissions reductions resulting from cogeneration of electricity that replaces the Czech Energy Agency's coal-produced electricity under USIJI and Section 1605(b) of the U.S. Energy Policy Act. They are strictly claiming CO_2 reductions that occur at the Bynov plant site.

Uncertainties affecting emissions:

- The Czech economy, although relatively stable over the last few years, is still an economy in transition and could potentially take a turn for the worse in the next few years if there are significant price shocks on the world market. It could also take a turn for the better. According to most economic forecasts, it is expected that it will be fifteen years or so before the Czech economy will fully turn around. Therefore, no significant increases in heat demand in Decin are anticipated over the life of the project.
- The Bynov plant is located in a small valley along the Elbe River. With little space to expand in the valley, it is unlikely that housing will increase or new commercial facilities will locate in the Bynov district. As a result, the demand on the Bynov plant is unlikely to change dramatically over the next twenty-five years.

Potential factors that could affect GHG emissions in the future:

- If the City of Decin were to opt to shut down the Bynov plant and shift the heating load to a coal-fired facility, the GHG emission reductions achieved previously would be lost. The City of Decin, however, was instrumental in obtaining the connection to the natural gas pipeline and has actively pursued interested parties to participate in the project, including the Center for Clean Air Policy. With such a strong commitment to the project, it is unlikely that the City would alter its plans in the future. In addition, because the distribution network of each plant in Decin is independent of the other four district heating plants, a large new facility would have to be built to link all five district heating plants together. Such a large facility would clearly be very expensive and is thus an unlikely option. Even so, guarantees for the U.S. utility investment and for the CO_2 emission reductions have been included in the agreements negotiated with the City.

Secondary effects:

A secondary effect of the project is those reductions which are not being counted as JI reductions but nevertheless are achieved. Some of the electricity that is generated by the Czech Energy Agency (CEZ), which supplies more than 80 percent of the Czech Republic's electricity, is being replaced by electricity generated by the Bynov plant.

The cogeneration facility will generate more than 25 GWh of electricity each year. The net CO_2 savings that accrue from 'backing out' CEZ electricity were calculated at 32,167 tons of CO_2 for the first year (see Table 1). Although the fuel sources upon which CEZ draws for electricity production include nuclear, coal, and hydroelectric, the power that is being replaced from the CEZ system is mid-load and peaking power, and all emissions reductions achieved will come from coal-fired units.

Taking the total coal consumption and the total electricity production from coal from CEZ, an average CO_2 emission rate/kWh is calculated:

$$[(29{,}000{,}000 \text{ tons lignite})\ (32.9 \text{ percent carbon}) + (600{,}000 \text{ tons hard coal})\ (67.4 \text{ percent carbon})] \times 3.667\ CO_2 \text{ emission factor} = 36{,}469{,}782 \text{ tons } CO_2,$$

$$(36{,}469{,}782 \text{ tons } CO_2)\ /\ (29{,}604 \text{ Gwh electricity from coal}) = 1.23 \text{ kg/kWh}.$$

These reductions should still be counted in the national inventory because they are not being claimed under a joint implementation project. CEZ's total coal consumption should be reduced accordingly. Thus, the data being used for the national inventory actually includes some reductions which arose from JI.

4. *Points to Consider*

4.1 Key questions regarding baselines:

(a) What is the existing baseline?

The calculation of current greenhouse gas emissions may be a simple, straightforward process in energy sector JI projects, as in the case of Decin.

More difficulty lies, however, in projecting relevant data for the future, such as, what would the emissions be over time in the absence of the project, what future energy demand will be, and the future growth of the economy and the area.

(i) What would the emissions be without the project? In the case of the Bynov plant, compliance with the Czech Clean Air Act would force a change at Bynov in order to limit its SO_2 emissions. It was demonstrated that the Clean Air Act could be complied with by switching to hard, low sulfur coal (see footnote 2). Although this would decrease SO_2 emissions, CO_2 emissions would barely change (see Table 1). In this case, then, the baseline GHG emissions were not expected to change significantly because of legal regulations.

(ii) Is the future demand flat or growing? The estimate of future energy demand was affected by existing regulations mandating the installation of thermostats and other energy efficiency improvements over the next five years. Thus, demand was estimated to decrease by 20 percent. During the same five years, however, it is expected that new homes will be connected to the system, increasing demand by 7 percent. These influences on demand have been taken into account in the projected future demand.

(iii) How will economic growth affect future demand? It is especially difficult to predict growth. This is particularly true in the context of a country with an economy in transition. Growth in the locality of the project can be affected by many factors. It is necessary, therefore, to establish more than one reference scenario, such as low growth, high growth, and the predicted baseline. In this case, the topography of the area gives little space for expansion. As mentioned above, growth in the heating district is not expected to change dramatically over the next twenty-five years.

(b) Is the poject included in the country's baseline?

JI projects are necessarily tied to the national baseline. The proponents in each potential JI project must ensure that the proposed project site has been recognized in the national baseline at the same emission level as they have estimated. National authorities must ensure that GHG reductions are subtracted from emissions counted in the national inventory if the reductions are to be recognized under established policies. The connection between national baselines and JI project baselines demonstrates the importance of an accepted, standard methodology that can ensure that the work of those estimating national baselines and inventories and those estimating baselines and reductions from joint implementation is coordinated.

(c) Should the baseline be changeable?

An important issue which arises frequently is whether the baseline should be changeable. The question arises when a starting assumption for a project is changed. For example, if the government changes a regulation five years after a project with a 20-year life span has started and requires a certain emission limit that was not required when the project was initiated. Investors could potentially lose their greenhouse gas credits if the baseline for the remaining years were to change. A changeable baseline could strongly discourage investment if stakeholders believe the baseline will be revisited, as they risk losing the entire investment. Introducing changes in the baseline is thus considered to be an unwise method of adjusting to changes. Instead, changes that are reasonably unforeseen should be taken into account, if possible, in project implementation, and the baselines should remain as originally agreed upon between the partners and hosts.

(d) Risks to the project

There is a risk in any JI project of not achieving the reductions as planned. Risks to the Bynov project include a plant shutdown, replacement of the district heating system by individual home heating, and better-than-expected demand-side management. The slim possibility of a plant shutdown was already mentioned above. Individual home heating would be less efficient and more expensive than with the Bynov project, so it does not constitute a significant risk. As for demand-side management, it is possible that individuals could take significant measures to insulate their apartments and windows. By taking strong (although costly) measures, residents could reduce the demand for heat by as much as 50 percent. In order to plan for this possibility, estimates of the most likely level of demand-side management actions were made in the engineering feasibility study, and a decreasing level of demand was taken into account in the overall emissions estimate (see Table 1), stabilizing by the year 2002.

(e) Monitoring

After the project is implemented, CO_2 emissions will be calculated using a simple throughput analysis. Annual consumption of natural gas will be drawn from the natural gas monitor used to determine payments for the gas supply. Using a value for the fixed carbon content for natural gas from the U.S. Congressional Office of Technology Assessment, CO_2 emissions and emissions reductions will be calculated for each engine and boiler at the plant. CO_2 emissions will be monitored periodically throughout the year with an annual report to be completed at the end of each year of the project. The annual CO_2 emissions will be certified by the Czech Ministry of Environment.

It is important that the project proponents also monitor the policies of the Czech and U.S. governments on scoring CO_2 emissions reductions relative to the Czech and U.S. national climate plans and inventories.

(f) Verification

Verification of emissions and reductions by an independent, nongovernmental third party lends credibility to the reductions claimed by a JI project. The World Resources Institute will review and assess the following elements:

- The project baseline developed by the City of Decin, Bruun & Sorensen, and the Center for Clean Air Policy
- The projected CO_2 emissions forecasts for 5 and 10 years for two scenarios (business as usual and compliance with the Czech environmental laws)
- A report prepared by the above parties on potential leakage problems, including shifting the existing load to other sources of heat supply and potential changes in overall emissions from other heating plants owned by the same newly privatized heating enterprise
- Czech government policy on scoring of carbon dioxide emissions reductions from the Bynov plant relative to the Czech national plan and country study
- Monitoring strategy and techniques proposed (could be CEM or fuel throughput analysis)

References

Portions of this paper are adapted from the Decin project's Application to the USIJI, prepared by CCAP.

The Clean Air Act, Law No. 309/1991 S.B.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Modelling Impacts of Measures for the Polish Country Study

Henryk Gaj

Polish Foundation for Energy Efficiency,
ul. Górskiego 7, 00-033 Warszawa, Poland

Abstract—As Poland has signed and ratified the Framework Convention on Climate Change (FCCC), and participates in the US Country Studies Program, proper methodology for modelling the response of the economic system to the greenhouse gases (GHG) abatement measures should be developed in Poland. The scheme of the Polish Country Study modelling system as well as the modelling algorithm of creating GHG abatement scenarios at the country level are presented. The well known problem of the consistency of bottom-up and top-down studies has provoked a wide scientific discussion. Since both bottom-up and top-down modelling methodologies are used in our Country Study, the consistency and comparability of results are considered. It was found that a transparent definition of policy measures and modelled objects in both cases is helpful for understanding the results and for proper interpretation of the results. A pragmatic approach to the problem is presented.

Key-words: economy, energy, climate, greenhouse gas, model, cost, benefit, politics.

1. Introduction

Poland has signed and ratified the Framework Convention on Climate Change (FCCC), which influences the policy and the economy of the country. Certain obligations have already been taken, others, probably carrying greater economic impacts, will be taken in the future. This situation challenges politicians to make optimal decisions and policy and economic analysts to create an efficient decision support system. The later task requires developing a modelling methodology which addresses the problems that must be solved.

Two important areas may be distinguished, conducting the greenhouse gases (GHG) emission and sink inventory and creating economic scenarios of GHG abatement and the adaptation of society to the anticipated climate changes.

These areas are covered by the US Country Studies Program, which was launched and financed by the US government. Poland participates in the US Country Studies Program and in turn launched the Polish Country Study (CS).

The CS requires the development of a modelling system to analyse reactions of the economy to applied policy measures.

2. Modelling System and Procedure for Creating Abatement Scenarios

In the CS the following sequence of questions should be answered:

- What are GHG abatement technological and technical options?
- What are possible and realistic policy measures that would stimulate GHG abatement?
- What is the likely reaction of the economy to the policy measures?
- What are possible GHG abatement scenarios at the economic subsystem level (sectoral scenarios)?
- What are the optimal combinations of abatement and policy measures for given objective functions at the entire economic system level (country scenarios)?

As the economic system is extremely complicated, simplified models are commonly used to analyse the system. The modelling system (MS) developed in and for the CS is presented in *Table 1.*

Table 1. General scheme of the Polish Country Study modelling system

Purpose	Level	Models	Modelling technique	Results: what	how
Data completion	Technological Sectoral Country	CS-DB CS-DB CS-DB	Data base	Data base for the Country Study	Technolog. data Economic data Emission char. Qualitat. data
Elaborating: • individual options • integrated options • sectoral scenarios	Sectoral: • Energy econ. • Power sector • Other sectors	EFOM ENPEP GACS	bottom-up	• technol. options • integrated options • sectoral scenarios	GHG red (t) Energy (t) Cost (t) NPC, IRR Sect. MC curve Qualitat. descript.
Creating the MERS	Country	DSM-NE	top-down	MERS	ME functions ME parameters Qualitat. descript.
Creating the MEAS • Defining collisions • Ranking options		CIA HIPRE3+	Decision analysis	• ranked sets of options • MC curves	Collisions GHG red. (t) Energy (t) Cost (t) Qualitat. descript.
• Defining policy measures to activate options	Country	GACS DSM-NE	bottom-up top-down	Policy measures	Taxes, subsidies Custom duties Emission limits Techn. standards
• Identifying the ME impacts of the policy measures		DSM-NE Emis. Mod.	top-down	GHG reduction scenarios	ME functions ME parameters Qualitat. descript.
• Evaluating the reduction scenarios		CIA HIPRE3+	Decision analysis	Final set of ME reduction scenarios	ME functions ME parameters Qualitat. descript.

The entire MS is served by a data base specially organized for the Project. The data base gathers technological, economic, and emissions data for the abatement options. Qualitative descriptions of options are also included.

The analyses are carried out at two levels of the system: sectoral and by country. This fact determines the modelling methodology to be used. At the sectoral level the energy and power sectors play a significant role because 96 percent of CO_2 emissions are caused by burning fossil fuels. Two bottom-up models, EFOM (*CEC,* 1991) and ENPEP (*Buehring et al.,* 1991) are used by the energy and power teams of the CS. The other sectoral teams have been equipped with the GHG Abatement Cost Spreadsheet (GACS) (*Gaj,* 1994). The GACS was elaborated especially for the Country Study. The methodology of the costing procedure is based on the concepts of cost-benefit analysis. Individual technological options are the basis for further analysis. That is why they should be examined in detail at the beginning.

The set of individual options should be tested by generating internally coherent sectoral scenarios. Collisions and overlaps of options should be eliminated. EFOM and ENPEP models are proper tools for this purpose. Step curves of marginal costs and a qualitative description of the scenarios are the expected output of the sectoral analysis. Additionally, GHG emission, energy consumption, and cost-time functions are required for further analysis at the country level (see the Sectoral Output block in *Fig. 1*).

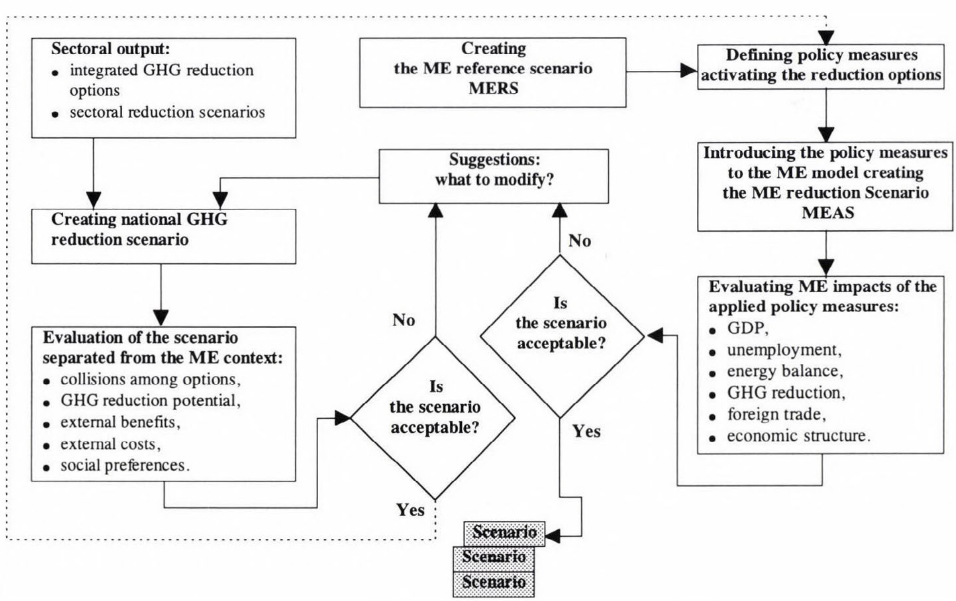


Fig. 1. Simplified algorithm of creating the GHG reduction scenario at the country level.

The country level activity starts from creating the Macro-Economic Reference Scenario[1] (MERS) defined with basic Macro-Economic (ME) functions and parameters.

The Dynamic Simulation Model of National Economy (DSM-NE) (*Radwański et al.,* 1993) was selected to be the main modelling tool at the country level. The model belongs to the top-down family. Its methodology follows the general equilibrium philosophy.

Next, the Macro-Economic Abatement Scenarios (MEAS) are being developed based on the sectoral abatement scenarios and the MERS. The procedure for creating the MEAS starts with combining the sectoral scenarios with the country size abatement scenario. Two Decision Analysis models and heuristic methods are used to detect collisions and overlaps among the sectoral scenarios. These models are the Cross Impacts Analysis (CIA) (*Radwański,* 1995) and the Hierarchical Preferences (HIPRE3+).

The CIA model was developed within the framework of the CS. The model enables analysts to estimate interrelations among probabilities of a given set of events while the events are activated stochastically. The model is coded as an EXCEL 5 spreadsheet. The HIPRE3+ is commercial Decision Support System (DSS) software distributed by Santa Monica Software Co. of California, USA.

Next, policy measures are defined for the resulting combined country size abatement scenario and the MERS to activate a given set of abatement options. The DSM–NE and GACS models are employed at this stage of work. The DSM–NE top-down model indicates the ME impacts of policy measures while GACS allows the analyst to estimate how a given set of policy measures influences the costs of options at the microeconomic level.

The resulting MEAS is estimated with key ME criteria (GDP, unemployment, energy balance, energy security, GHG emission reduction, foreign trade, inflation, and economic structure). The criteria and their weights should be discussed with policymakers and approved by them. The procedure is modified and repeated until it generates an acceptable MEAS.

3. Sectoral and Country Levels Consistency

Very often significant differences in the results of bottom-up and top-down analyses are reported. As a rule, the bottom-up modelling indicates small costs of GHG abatement or even benefits, while the top-down analysis indicates significant costs. This problem should be faced in the CS because both modelling techniques are used.

---

[1] The problem of how to create the MERS was discussed during the Workshop. Although a single MERS is recommended for use and application to the Country Study *LBL* (1995), a variant MERS may be also considered.

The common interpretation of GHG emissions reduction costs is presented in *Fig. 2.* The upper diagram shows the marginal costs of emissions reduction as a function of the reduction. The step curve is constructed with abatement options. The options below the zero cost line are economically effective, while those above carry positive costs. The solid line in the lower diagram illustrates the total costs of the emission reduction. For the given example, if A, B, C, and D options were put into practice, economic losses would result. This situation applies to the initial state of the economy, without GHG abatement policy measures.

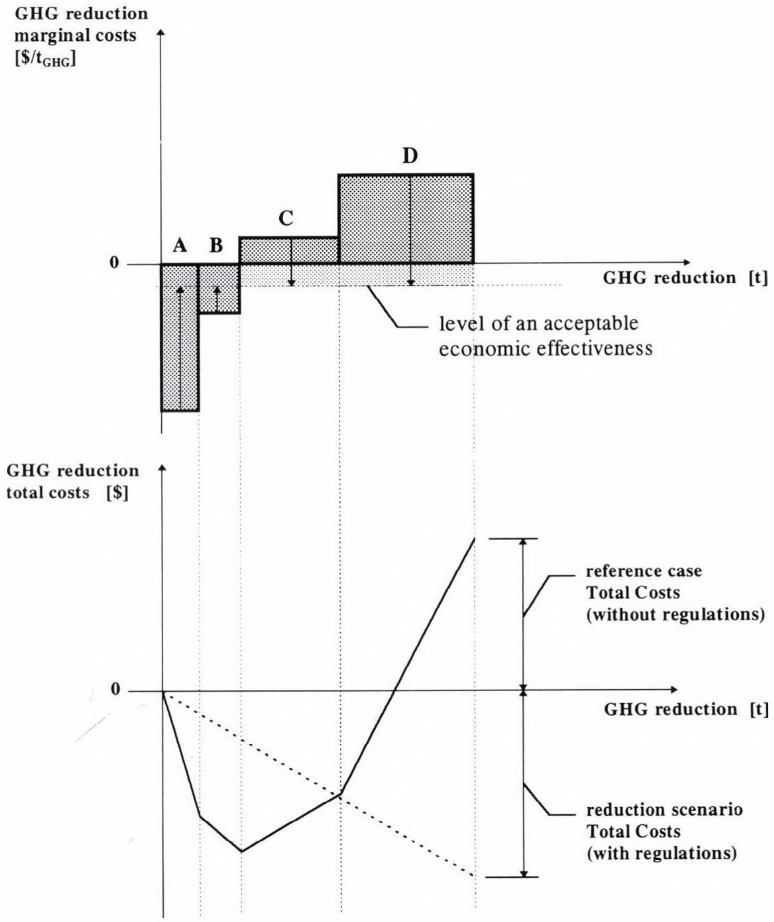


Fig. 2. Costs of GHG reduction economic activities.

It seems evident that unprofitable options (C and D in the example) have no chance to be launched, because the decisions are taken át the microeconomic level. It is suggested that an economic effectiveness of C and D options may be improved by proper policy measures (for example, carbon tax decreases fuel costs for the coal-to-gas switching projects). If the policy measures shift costs of options to the level of acceptable economic effectiveness (see the upper diagram in Fig. 2), then they have a chance to be launched. The total benefit in this case is indicated by the dashed line at the lower diagram in Fig. 2.

Because the above example illustrates in a simplified way a bottom-up procedure it seems evident that the procedures may document only benefits, if limited to the GHG abatement activities. If the subsystem is modelled by the bottom-up procedure, wider distribution of costs and benefits may appear, and positive costs may result. Such a case is illustrated in *Fig. 3*.

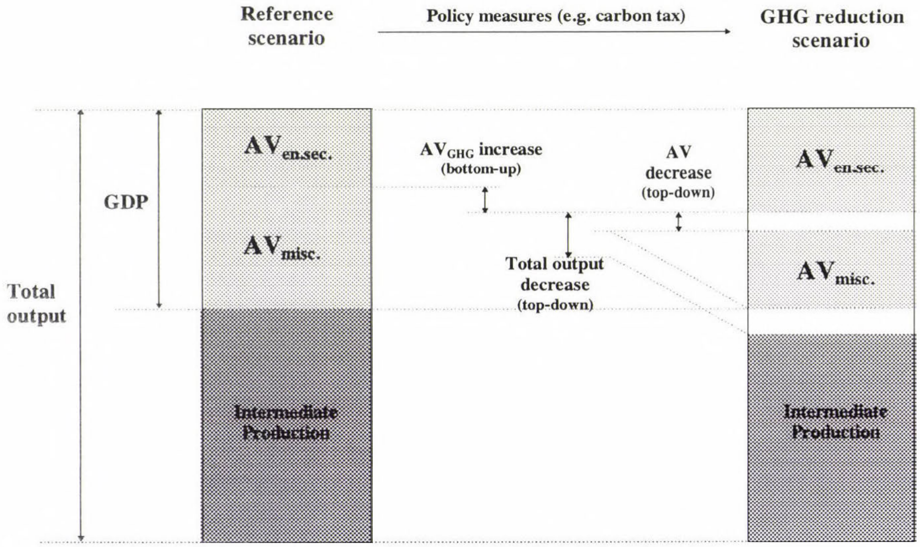


Fig. 3. Possible reaction of the national economy on regulations.

In this case, the entire economy is considered. It may generally be assumed that the reference scenario (left bar) is optimally constructed. This implies that additional regulations may only spoil it. That is just a case. Applied policy measures (for example, a carbon tax) certainly activate GHG abatement economic activities, resulting in additional added value in the energy sector, but simultaneously inhibiting activity in other sectors to an even greater extent. The same may be said about the total output (see Fig. 3).

The above explanation shows that observed bottom-up–top-down disagreement may result from the fact that the results in one or both cases are not interpreted precisely enough. It would be valuable to distinguish (to tag somehow) the GHG abatement activities in the top-down model. This would enable a more precise visualization of the bottom-up procedure in the frame of the top-down model. On the other hand, it could be difficult to do because top-down models are usually highly aggregated.

This article describes the subject matter quite generally without touching the details. The modelling system elaborated in the Polish Country Study, as well as the bottom-up versus top-down consistency interpretation, will eventually be verified experimentally while preparing the GHG abatement strategy for the country.

Acknowledgements—This work was sponsored by the US Country Studies Program, Polish Country Study to Address Climate Changes.

References

Buehring, W.A., Hamilton, B.P., Guziel, K.A., and *Cirillo, R.R.*, 1991: *ENPEP: An Integrated Approach for Modelling Energy Systems*. Argonne National Laboratory, Argonne IL USA.

Commission of the European Communities, 1991: *Cost-Effectiveness Analysis of CO_2 Reduction Options*. Report for the Commission of the European Communities DG XII, JOULE Programme. Models for energy and environment. CEC.

Gaj, H., 1994: *Development of National Cost Estimation Methodology for the GHG Reduction Options and Strategies*. Polish Foundation for Energy Efficiency, Warsaw.

Lawrence Berkeley Laboratory, 1995: *Guidance for Mitigation Assessment: Version 2.0*. Lawrence Berkeley Laboratory, Berkeley CA USA.

Radwański, E., Gromadziński, A., Hille, E., Skowroński, P., and *Szukalski, St.*, 1993: *Case Study of Greenhouse Gas Emission in Poland*. Polish Foundation for Energy Efficiency, Warsaw.

Radwański, E., 1995: *Country Study* Report No. 5. Polish Foundation for Energy Efficiency, Warsaw.

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Joint Implementation Pilot Project on On-site Energy Advice for Local Communities

Zoltán Lontay

EGI-Contracting/Engineering Co. Ltd.,
Bem rkp. 33-34, H–1027 Budapest, Hungary

Abstract—The concept of joint implementation[1] (JI) was developed to help countries work cooperately on climate change. It raises enthusiasm as well as criticism. It is promoted by many industrialized nations and feared by many developing ones. The concept has been discussed in various forums, but no agreement has been achieved yet. A Dutch-Hungarian joint implementation simulation study is being performed to make a contribution to the debate. It is based on the results of the Dutch-Hungarian energy efficiency cooperation of recent years, mainly on the findings of the project On-site Energy Advice for Communities in Hungary. After presenting some general ideas about JI the paper describes the results achieved by the study so far. JI is neither a panacea nor a new trick of the rich countries to assure better access to the Earth's limited resources. JI is a promising instrument of stabilizing greenhouse gas emissions, if it is done in a cost-effective way, and if benefits are accounted in a fair way.

Key-words: joint implementation, simulation study, Dutch-Hungarian cooperation.

1. Introduction

The idea of joint implementation (JI) was developed in the late 1980s as a possible strategy for cost-effective greenhouse gas (GHG) emissions abatement. It has been in the focus of heavy debate since its introduction. While all nations agree that industrialized countries shall have a higher contribution to combating climate change, the developing countries are not willing to pay a price for that. The issue is politically sensitive. Extreme emotions appear—without a thorough check of the idea itself.

---

[1] *Joint implementation* means that more prosperous countries and developing countries act together to achieve CO_2 emissions reduction. The rich countries invest in emissions reduction measures in the developing countries. In return, CO_2 reduction is credited to the investing country.

It is widely accepted that improving energy efficiency is one of the most effective instruments of reducing GHG emissions. Within the framework of bilateral assistance, the Dutch Government has been supporting energy efficiency programs in Central Europe recently and have come to the conclusion that running energy efficiency programs could be and should be tested for compliance with JI.

NOVEM, the Dutch Government's energy efficiency agency and EGI, a Hungarian consultant, were assigned to perform a simulation study. They are in the process of evaluating a successful energy efficiency project On-site Energy Advice for Communities in Hungary from the standpoint of JI.

The paper gives an overview of JI, then preliminary findings of the simulation study are introduced. After outlining future plans, the conclusions of the work are summarized.

2. Views, Thoughts about JI

2.1 Actors and Interests

It is of basic importance to understand who are the actors in the JI field, and what are their specific interests.

The United Nations Framework Convention on Climate Change was adopted by countries who are represented by their governments. The governments are responsible for the greenhouse gas inventories, for the development and implementation of abatement policies, and for communication on the implementation of commitments. If JI is accepted, it is only the governments who will acknowledge CO_2 credits.

The whole process is coordinated and monitored by a specialized body of the United Nations. It is expected that the UN will encourage its member states to make further commitments and will supervise implementation of the commitments. Failures will be reported to the international community.

The governments' basic interest is to comply with their commitments at minimal cost. Their performance is monitored mainly by the greenhouse gas inventories. This is why the governments (either donor or host) will never be interested in actions which are not reflected in their inventories.

The governments, under the pressure of their international obligations, will take various measures to limit the greenhouse gas emissions of their energy users. In addition to regulation and education they will apply economic instruments, such as taxing energy consumption (example, by a carbon tax) or promoting conservation from state funds. It is evident that both solutions create additional costs for the countries.

Costs of CO_2 abatement can be determined by a nonlinear function. The graph of such a function is shown by *Fig. 1*.

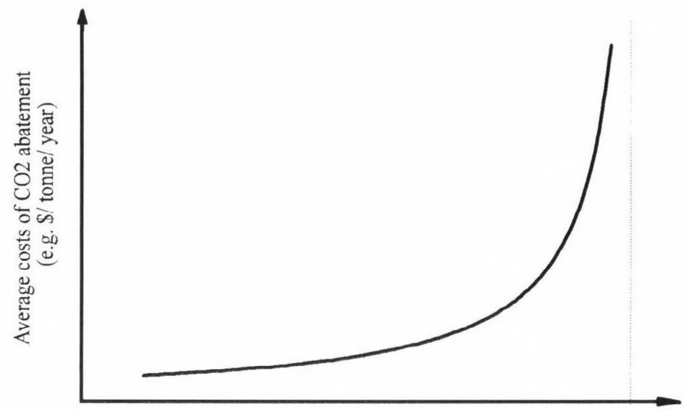


Fig. 1. The shape of CO_2 abatement cost function.

On the vertical axis of the graph average costs are shown, which include both one-time first costs of the measures and the continuously occurring variable costs[2]. On the horizontal axis the total amount of abated CO_2 is shown compared to the reference situation (the situation without the considered abatement actions). The function is asymptotic, because even if all the energy production is switched to renewable sources, there remains some emission which cannot be abated.

The cost function of the individual countries is different. It is very likely that abatement costs are higher and potentials lower for the industrialized countries, as illustrated by *Fig. 2.*

This cost difference is the main driving force for JI.

Within the individual countries, on the 'micro' level there are two important groups of actors. The energy producers (who may be the end-users at the same time) make efforts, under the pressure of their national energy policy, to reduce their emissions. Their successful efforts are rewarded either by reduced taxes or by subsidies. They may rely on entrepreneurs or service companies, who offer CO_2 abatement services. The energy producers are clearly interested in reducing their emissions at minimum cost, and in maximising side-effects.

If the countries really want to commit themselves to sustainable development, sooner or later a market of emissions and abatement services will develop. This is true for both the individual countries and the international community. JI will create an international market of CO_2 abatement and related

[2] A building insulation program, for example, needs investment at the beginning, and maintenance for the lifetime of the building. One can get average costs by dividing lifetime savings by lifetime costs (present values should be used).

services and technologies, where the value of emissions and services is expressed in money terms.

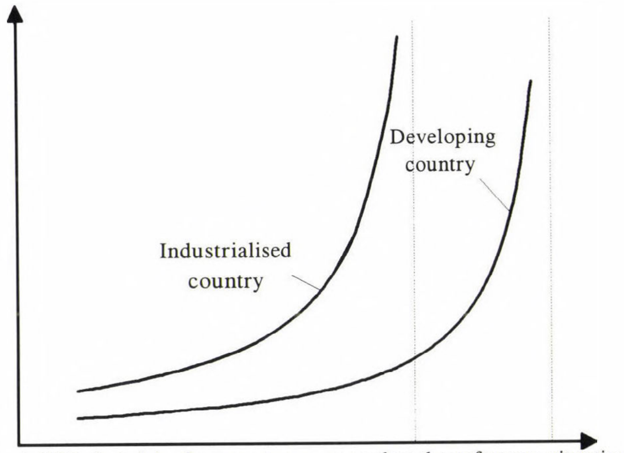


Fig. 2. Cost functions of industrialised and developing countries. The vertical axis shows the average cost of CO_2 abatement ($/ton per yr).

2.2 Possible Methods of Joint Action

If it is accepted that changes in CO_2 emissions can be brought into connection with (money) values, two basic options appear:

(1) The industrialized countries buy emission credits from the developing countries.

(2) According to the JI concept, the industrialized countries provide in-kind abatement services to the developing countries, offering technology as well as capital.

The idea of trading with emission credits may raise understandable criticism. The developing countries may claim that their elementary rights to the resources of the Earth are (again) endangered, and the rich countries can get everything for money.

It can be stated that joint implementation, as practiced by the original concept, is politically more acceptable and simultaneously more cost-effective. JI may also have several beneficial side-effects, such as better cooperation among the nations, common learning during the joint efforts, and the development of a higher responsibility for the Earth.

2.3 Lifetime of JI Measures

The author is convinced that eternal credits shall be not considered. On the one hand it is politically not acceptable. By selling eternal CO_2 credits, poor countries would lose the possibility of any later economic growth. It would, in extreme situations, endanger their existence.

On the other hand, within the framework of JI, CO_2 abatement will be achieved by technical measures (nontechnical measures are not good applicants for JI—see later sections). All technical measures have physical lifetimes, at the end of which a new situation occurs, demanding a conclusion or renegotiation of the project.

In addition to the above considerations, a new lifetime definition can be applied to JI projects. It is based on the offsetting effect of a potential base scenario.

We can assume that at the beginning the developing countries have higher emission limits (commitments) than actual emission levels. They have CO_2 emission reserves. Later, their emission levels increase because of the growth of their economy or population. If they do not take measures to decrease emissions, they hit the limit at a future time T, as illustrated in *Fig. 3*.

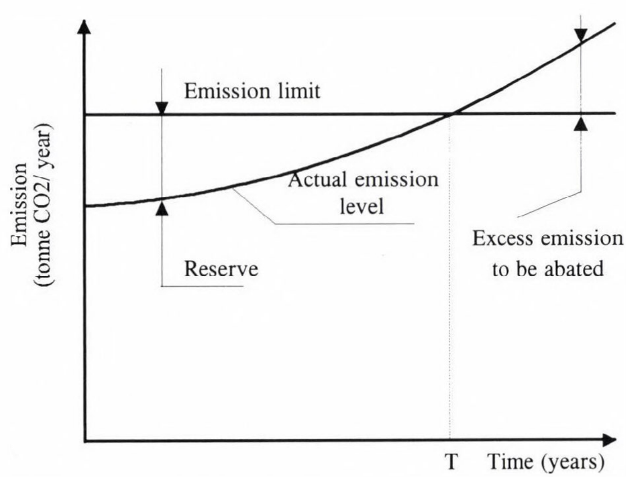


Fig. 3. Growth of emission of a developing country.

At this time, the country has no other choice than to start investing in CO_2 abatement, according to the excess emission. The dotted line of *Fig. 4* shows the abatement activities of the country in the baseline or JI-free scenario.

JI projects can be illustrated on the graph by a stepped curve, as abatement capacities are installed in finite quantities. The lifetime of each JI project can be determined by the intersection of this JI curve with the reserve curve. At the end of the lifetime determined this way the credits have to be withdrawn or the conditions of the credits renegotiated.

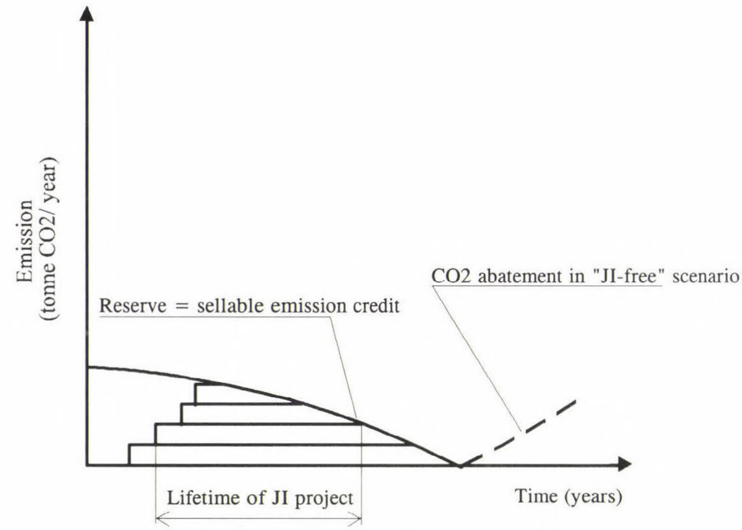


Fig. 4. Definition of lifetime in JI projects.

2.4 About Cream-Skimming

Figs. 1 and 2 show the nonlinear character of abatement costs. The phenomenon when the developed nations use up the low-cost opportunities may be called 'cream-skimming'.

Some developing countries criticize JI in fear of this cream-skimming effect. They worry that well-informed and well-prepared industrialized countries may quickly enter into JI agreements, leaving the expensive solutions to the poor countries.

It must be emphasized that JI only makes sense if benefits are produced for both the donor and the host countries. The author believes that mutual benefits are not only necessary, but achievable, too.

2.5 Money and Credit Flows

In trading with emission credits (option 1 in Section 2.2), money and credit flows are simple, as shown by *Fig. 5*. In-country management of these flows is the responsibility of the individual countries. The government of the donor country must find a way to gather money (for example, through carbon taxes) to buy the credits, while the host country must be sure that emission reserves are available or can be created at low cost.

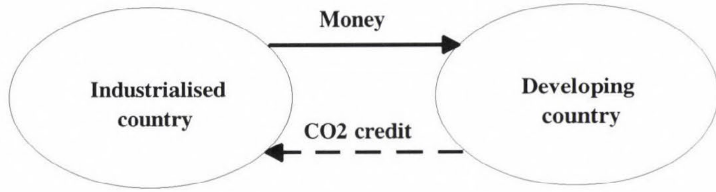


Fig. 5. Trading with emission credits.

The money and credit flows are more complicated with JI. The projects are developed by microlevel organizations of the donor and host countries (being encouraged by their governments). The scope of microlevel organizations includes entrepreneurs, consultants, NGOs, and so forth, of the donor countries and energy producers of the host country. Entrepreneurs, consultants, NGOs, and so forth of the host country may also participate in the development and implementation of projects as subcontractors to the organizations of the donor countries.

The costs of the donor country's organizations must be covered by the donor state, for example through a JI fund. This fund can be created from fees of tradable emission permits, from carbon taxes, or from budget money. It is also possible that the microlevel organizations earn CO_2 credits not for the state, but for themselves. In this case all or part of the credits offered by the host country is given to the implementing microlevel organization.

The energy producer of the host country benefits from the transaction primarily by the side effects, such as reduced fuel bills, installed cogeneration capacity, or refurbished buildings. If the project succeeds in abating CO_2, the host country's government is notified. In exchange, the government may require a part of the credit or a part of the side benefits. It is also possible that the host government simply charges a fee on the transaction. A possible flow of monies and credits is shown in *Fig. 6*.

Depending on the policy instruments applied in the donor and host countries, a variety of possible money and credit flows can be envisaged.

It is very difficult to develop pure CO_2 projects. Additional benefits may and should always be present. If the value of the additional benefits is significant compared to the value of the basic benefit (CO_2 abatement), JI projects shall be financed by the organizations of the donor and host countries together.

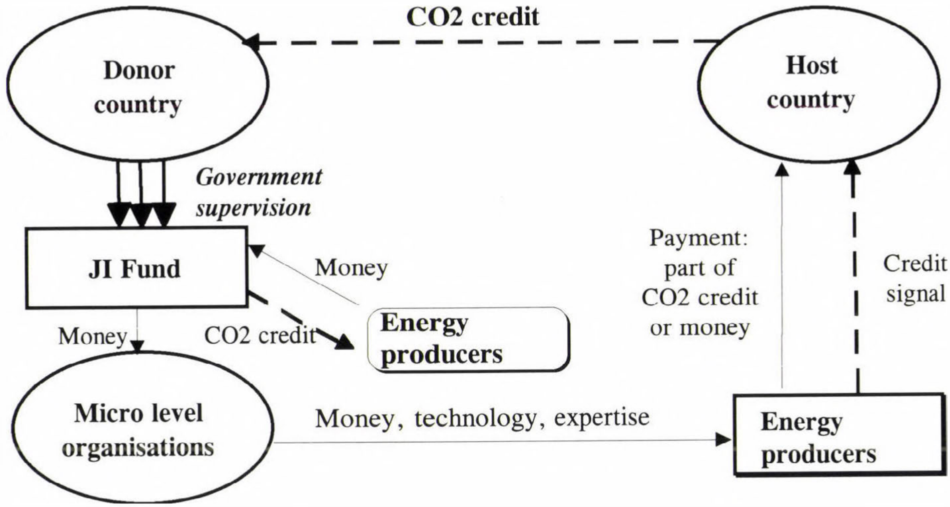


Fig. 6. Money and credit flows in JI transactions.

2.6 Criteria of Successful JI Projects

JI projects must have the following main characteristics:

- Cost-effectiveness; both the investment and the operational costs must be as Low as possible.
- Accountability and attributability. Any intervention into an energy system may induce a series of changes. With JI projects the main target is the reduction of CO_2 emissions, although other effects are always present, too. It is very important to understand what changes are induced by the interventions and what are the quantitative results. JI projects can be successful only if the results are unambiguous, and can be either measured or calculated by a method agreed by to all parties prior to the implementation of the project.
- Appropriate size. In a JI project a number of actors is involved from the micro and macro level of the participating countries, adding to the management costs. These costs do not grow proportionally with the size of the project, so the specific management costs are lower with bigger projects.
- Compliance with state guidelines. If good progress occurs in the JI field, both the donor and the host countries will probably issue guidelines. The donor countries will, for example, certainly specify the rules of allocating money from the national JI fund. The governments of the developing countries will set the criteria of accepting request for CO_2 credits.

2.7 Similarities between JI and Performance Contracting

Energy performance contracting (EPC) for energy efficiency and environmental control is a technique successfully applied in some countries. Vendors, called energy service companies (ESCOs) invest in the energy systems of the clients. They provide expertise, technology, and capital. Their efforts are rewarded by a part of the savings generated by the interventions of the ESCO.

There are apparent similarities between JI and EPC. Both approaches do the following:

- Utilize the capabilities of well-prepared parties for the benefit of both parties,
- Share achievements,
- Quantify achievements in an agreed manner, and
- Utilize the synergy effect.

3. Review of Past Dutch Energy Efficiency Efforts in Hungary

3.1 Bilateral Assistance Program for Hungary in the Energy Field

The Netherlands have been offering assistance to Hungary in the energy efficiency field for several years. At the beginning, selected industrial sectors, such as the dairy, meat processing, milling, and brewing industries, were involved. Later, a national CHP study was prepared to assess the potential for small-scale cogeneration in Hungary.

Since 1993, the main focus of the program has been the local communities, based on the recognition that while the share of the communities in the country's energy consumption continuously increases, the capabilities for addressing the challenges are often missing.

3.2 Community Advice Program

3.2.1 Description

Within the framework of the program, On-site Energy Advice for Communities in Hungary, assistance is offered to selected local governments (municipalities). An expert team contacts them and offers a menu of the following items:

- Assistance in developing local energy strategies,
- Energy auditing of selected public buildings,
- Developing energy conservation projects,
- Surveying local district heating systems,

- Evaluating the local government's energy management activities,
- Assisting in energy-related communication with the inhabitants,
- Preparing an energy-efficiency working plan,
- Surveying the public lighting system,
- Assisting in negotiations with suppliers.

The local governments choose from the menu according to their specific needs. Then the team studies the local situation, takes measurements, conducts interviews with actors of the local energy field, and so forth. They summarize their findings in a written report, which answers such questions as 'what to do?', 'what to expect?', and 'what does it cost?'.

The project is supervised by a steering committee, composed of members from the relevant ministries. The expert team's work is commented on and assisted by an advisory board, which represents the general interests of the local energy field. The whole management process is transparent; the findings of the program are disseminated to all relevant actors of the field.

The experts keep their eyes on the local governments after reporting, too. They maintain pressure on them in order to push the implementation of proposals.

3.2.2 Summary of proposals

In the framework of the program 24 communities have been audited and advised. More than one hundred proposals have been undertaken. Some proposals relate to educational and awareness development changes, or to the introduction of more careful energy management. The results of these proposals cannot be quantified.

Altogether 78 quantifiable proposals have been presented to the local governments. If 100 percent of them are implemented, an energy saving of 191,409 GJ/year can be achieved, at an investment cost of 370,000,000 HUF (equivalent to about 7 million NLG). This energy savings reduces Hungarian CO_2 emissions by 12,810 tonne/year.

Of course, energy conservation is a worthwhile investment without JI, too. We have checked what part of the investment costs are justified by energy savings alone. We have come to the conclusion that under the specific conditions of the selected local communities and the economic background of early 1995 Hungary, roughly three-fourths of the costs are justified by energy savings and only one-fourth of the costs must be financed by JI.

3.2.3 Status of implementation

The status of implementation of proposals is being reviewed by EGI. The following preliminary observations can be made:

- The communities have implemented 10–90 percent of the proposals so far.
- Because of the practice of yearly planning, some projects can be implemented only in 1995 and 1996.
- Some communities underestimate the importance of energy efficiency and the potential for cost saving. This is why they neglect implementation of EE projects.
- Other communities have realised the importance of energy efficiency and do their best to succeed in this field.
- The legal and economic environment still does not properly encourage energy-efficiency efforts.

3.2.4 Lessons learned

The most important lessons learned during the community advice program can be summarized as follows:

- With respect to the situation in Hungary (scarcity of capital and awareness), the program focused on low-cost measures, mainly on education and better housekeeping.
- There is a significant potential for energy saving in Hungarian communities. A part of this potential can probably be channelled to JI.
- Educational and behavioural projects cannot be directly used as JI projects, because the verification of savings and attribution of results is ambiguous.
- Investment-type projects, such as cogeneration or boilerhouse refurbishment, seem to best suit the JI concept.
- If more complicated measures are considered for JI (for example, the introduction of energy management), a reliable monitoring system must be established before implementing the JI project.

4. Plans for 1995

4.1 Energy-efficiency Projects

Within the framework of Dutch-Hungarian bilateral cooperation further energy-efficiency projects are foreseen for 1995, including the following:

- Continuation of the community advice program,
- Implementation of a demonstration CHP[3] project (simultaneous generation of heat and electricity by a gas engine plant in a district heating system),

[3] CHP = Combined Heat and Power generation

- Implementation of a demonstration DSM[4] project,
- Introduction of the monitoring and targeting approach to several communities.

4.2 The JI Approach Superimposed on the Program

A JI approach will be superimposed on the above program. Answers for the following questions will be sought:

- Which emissions reductions of greenhouse gases result from the project?
- Which local benefits does the project entail?
- What are the costs to reduce CO_2 (per tonne)?
- How can and should the emission reductions be attributed to the participants?
- What kind of projects are eligible for JI?
- What transfer of technology and contribution to local capacity building have taken place?
- How has the monitoring, reporting, and, possibly, verification of claimed results been arranged?
- What organizational structure has been established?

5. Conclusion

Based on the considerations of the previous chapters and on the findings of the Dutch-Hungarian energy-efficiency program the following conclusions can be drawn:

- Well-designed JI projects can earn benefits for both the donor and the host countries.
- Trading with emissions credits in the international arena probably will not be supported. At the same time the introduction of JI requires that some kind of value is given to the credits, and this value is expressed in money terms, too.
- The developing countries' CO_2 emissions reserves decrease with time if their economy or population grows. The industrialized countries should utilize JI opportunities quickly to win some time to prepare for more complicated actions.

---

[4] DSM = Demand Side Management (the energy utilities' activity on the demand side to improve energy efficiency)

- In addition to the main effect, that is, the abatement of CO_2 emissions, JI projects in general have important side-effects.
- As long as a developing country has free CO_2 emissions reserves, it is not interested in sharing the emissions credits with the donor country. Emissions credits have no practical value for the developing country, unless they can be traded for other projects. In this period the developing country is interested in the additional benefits.
- The reserves can be determined by modeling. The unreliability of models is the primary risk for the developing countries. If they overestimate their reserves and offer too much credit within the framework of JI cooperation, they can get into trouble, and be faced with unexpected abatement costs.
- The host countries must take into consideration the nonlinear character of abatement costs when they enter JI projects. Fair donor countries avoid cream-skimming.
- Each JI project has a lifetime, which is limited by the physical and moral depreciation.
- JI actions must be able to influence the emissions inventory of the developing countries. The method of accounting must be accepted by the relevant United Nations body.
- Only clearly defined, accountable, attributable interventions may be considered as JI projects. Small-scale interventions shall be excluded. The parties shall agree on all relevant conditions before implementing the project. The conditions must be clearly put down in a contract.
- JI projects are developed and implemented by microlevel organizations, while financing and the issue of credits is the responsibility of the governments. Both the donor and the host countries must work out the JI rules for their microlevel organizations.

Acknowledgements—The author wishes to offer his thanks to *Mr. Jord Neuteboom* of NOVEM and *Mr. István Kovacsics* of EGI for their valuable contributions, without which this paper could have never been accomplished.

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

Energy-Economic Modelling in Hungary

Sándor Molnár and **Tibor Takács**

Systemexpert Consulting Ltd.,
Mikoviny S. u. 2-4, 1037-Budapest, Hungary

Abstract—As a result of local and global environmental problems, most models of mid- and long-term energetic planning take into consideration the pollution processes caused by energy production, distribution, and consumption.

The most widely distributed energetic models are available in Hungary. Three of these models have already been tested and applied in the long-term planning of the Hungarian power supply system: LEAP, ENPEP and EFOM_ENV. Further models are also planned to be applied in the near future. Most of the electricity is generated by the power plants of the Hungarian Power Companies, a state-owned firm (which is planned to be privatized in the next years). In 1993, the Hungarian Power Companies elaborated a new strategy for the development of the power plant system, which includes all the possible combinations of capacity enlargement till 2010. As a consequence of international contracts, emissions (incl. greenhouse gas emissions) have to be radically decreased during this period. In the framework of a cooperation between Systemexpert Consulting Ltd. and the Environmental Department of the Hungarian Power Companies, the above mentioned three models were used as decision supporting tools. The LEAP is a scenario analyzing model evaluating and comparing some main alternatives from the viewpoint of costs and different environmental impacts. Two modules of the ENPEP system were applied: BALANCE and IMPACTS. BALANCE is a comprehensive model of the whole energy system, which follows the entire production verticum: extraction, transformation processes, transportation, distribution, and consumption. It is applicable if the modeller wishes to examine extraction and consumption in a common framework. If demand and supply meet, IMPACTS determines the environmental consequences, and the abatement strategy. EFOM_ENV is a linear programming model, in which constraints include limits on different types of emissions.

As a result, the models suggest that in the long-term the increasing demand can be covered by either a new atomic plant, or by a new plant based primarily on imported coal. A considerable share of existing (and relatively old) power plants still have to work, but they should be equipped by different abatement technologies.

Key-words: energy modelling, scenario analysis, air pollution, emission abatement.

1. Introduction

In 1993 the Hungarian Power Companies elaborated a new strategy for the development of the power plant system, which includes all possible combinations of capacity enlargement till 2010.

Hungary joined the Helsinki Convention, according to which participants had to decrease SO_2-emissions by 30% in the period 1980–1992. As a consequence of the economic recession and the exhaustion of domestic coal reserves, Hungary has overfulfilled this pledge; in 1980 the SO_2-emissions were 1633 kt which dropped to 892 kt by 1991. Environmental measures played only an insignificant role in this decrease. The ongoing international discussions aim at further significant decreases of SO_2-emissions. According to the present conception, the SO_2-emissions should be decreased 50–70% by 2005–2010 as compared with the present emission levels.

As far as greenhouse gases are concerned, Hungary has ratified the Framework Convention on Climate Change in December 1993. Applying Article 4.6 of this Convention, Hungary has undertaken that CO_2-emissions should return to the average level of 1985–1987 by 2000. The share of power generation in CO_2-emissions is normally around 40% in Hungary, therefore this aspect has to be taken into consideration in the planning of the power generation.

There are also specific prescribed limits on NO_x-emissions originating from the power plants of the Hungarian Power Companies. The level of NO_x-emission has to be decreased 25% by 2004. Furthermore, there is also a prescription for particulate emissions, according to which it has to be decreased 50% by 2004.

The purpose of energy modelling is to determine scenarios which assure the necessary emission reductions taking into consideration the mid and long-term increase of demand on electricity. The models have to determine which measures and investments would be necessary in Hungary to fulfill the above mentioned prescriptions. In our investigations we aimed at a comprehensive analysis of the whole energy supply system. The most widely distributed energetic models became available in Hungary, they were tested and compared (see *CMDI*, 1992).

2. Models Used in Energetic Planning in Hungary

In the framework of a cooperation between Systemexpert Consulting Ltd. and the Environmental Department of the Hungarian Power Companies, the following PC oriented models were adapted: the LEAP, the EFOM_ENV/GAMS and the ENPEP (see *Systemexpert,* 1994a and 1994b; *Systemexpert,* 1995a and 1995b). First we briefly outline these models.

2.1 The LEAP Model

The LEAP (Long-term Energy Alternatives Planning System) model was developed in the Boston Tellus Center of the Stockholm Environment Institute. It is a scenario analyzing model. The different long-run scenarios are evaluated from both economic and environmental points of view. In the development of LEAP the following methodological considerations were realized:

- Scenario approach (base case vs. policies),
- End-use, demand driven approach,
- Flexibility and user-friendliness, and
- Computer applications and data development should evolve together.

The relationship between data and analysis can be expressed as 'collect the data, then do the analysis.' For the environmental evaluation of the scenarios a special module called Environmental Data Base is connected to the program. The Environmental Data Base (EDB) provides a comprehensive summary of information linking energy production, conversion, and consumption activities to air and water emissions, and other environmental and health consequences. As a stand alone program, it is an easy-to-use, fully referenced and annotated compendium of energy related environmental statistics. The user can add additional data appropriate to local facilities or specific studies.

Linked with the LEAP Energy Scenario programs, the EDB provides the coefficients used by the Environmental program in computing the environmental consequences of alternative futures. The user stores and accesses an extensive set of quantitative and qualitative information about the environmental impacts of production and consumption activities. The EDB can be thought of as a two-dimensional matrix. The rows in the matrix, or source categories, are the activities (e.g., energy end-uses and energy production processes) that are the source of environmental emissions or impacts. The columns in the matrix are the resulting emissions and impacts, or effects categories. *Table 1* shows the default effect categories included in the Environmental Data Base at the moment.

2.2 The EFOM_ENV/GAMS Model

The model EFOM_ENV (Energy Flow Optimization Model) was developed by the Commission of European Communities DG XII over the past ten years, and is primarily used in the countries of the European Community. Unlike the earlier versions of the model, EFOM_ENV runs on PCs and this optimization model includes constraints on emissions of different pollutants as well. It is a continuous linear programming model. The constraints are as follows:

- Balance equations for blocks (Equilibria of in- and outflows),
- Capacity constraints,
- Minimum demand levels,
- Market allocation constraints (share of blocks or group of blocks in the production), and
- Constraints of emissions.

The balance equations include seasonal balances as well. The model is based on two steps load and generation duration curves. Since this is a rather rough approximation of the actual curves, we also tried to apply a five-step curve in the model. This leads to a considerable increase of model variables, but these

Table 1: Default effect categories in EDB

Air emissions	**Water effluents**	**Solid wastes**
Carbon dioxide	Solids	Mining waste
Non biogenic	Total	Inert
Biogenic	Suspended	Total
Carbon monoxide	Dissolved	Total
Total	Oxygen demand	Ash
Hydrocarbons	Biochemical	Total
Total	Chemical	Scrubber sludge
Aldehydes	Sulfates	Total
Benzene	Total	Radioactive
Tar	Metals	Low level (curies)
Volatile hydrocarbons	Total	Low level (volume)
Formaldehyde	Cadmium	
Organic acids	Chromium	**Occ health. safety**
Methane	Copper	Deaths
Hydrogen sulfide	Iron	Total
Total Metals	Mercury	Injuries
Lead	Zinc	Total
Arsenic	Salts	Work days lost
Boron	Total	Total
Cadmium	Nitrates	
Chromium	Total	
Mercury	Organic carbon	
Nickel	Total	
Zinc	Oil and grease	
Nitrogen oxides	Chlorides	
Total	Total	
Nitrous oxide	Ammonia	
Sulfur oxides	Total	
Total	Phosphates	
Sulfur dioxides	Total	
Toxic hydrocarbons	Cyanide	
Polycyclic organic molecules	Total	
Particulates	Radioactive	
Total	Tritium	
Size less than 10 microns	Activation & fission products	
Fugitive coal dust		
Radioactive		
Carbon 14		
Iodine 101 (elemental)		
Iodine 131 (nonelemental)		
Noble gases		
Radon		
Tritium		
Ammonia		
Total		
Thermal emissions		
Total		

computations did not change the results significantly. Therefore, we used rather the original model to spare time of model runs. The objective is the sum of discounted total costs. For every block the modeller may specify the applicable abatement technologies. The model selects those technologies that will be necessary to stay within the emission limits.

The last version of EFOM_ENV is written in the GAMS language (General Algebraic Modelling System). This modelling language is especially developed to handle large and complicated models.

2.3 The ENPEP Program System

The ENPEP (Energy and Power Evaluation Program) was developed by Argonne National Laboratory (USA). We have used two of its modules: the BALANCE and the IMPACTS. BALANCE is a comprehensive model of the whole energy system, which follows the entire production verticum: the extraction, the transformation processes, the transportation, the distribution, and the consumption. It is applicable if the modeller wishes to examine the extraction and consumption in a common framework. This comprehensiveness suggested the idea that BALANCE and IMPACTS together may be suitable for examining the environmental impacts of the whole energy system.

The BALANCE module is used to project the balance of energy supplies and demands for long-term through use of an energy flow network designed by the modeller. To find the equilibrium solution to your network, the model makes initial estimates of values of fuel importation and production quantities at the bottom of the network. After the initial estimates are made, the prices of fuel on each successive link going up the network are computed from the price equations defined by the various nodes. Next, the solutions to all the quantity equations associated with the nodes of your network are computed for successive links going down the network. If all equations in the network are satisfied by the initial estimated quantities, a solution to the model has been found. Otherwise, the quantities at the bottom of the network are automatically adjusted, and all equations are solved again. This iteration process continues until the proper values for the quantities at the bottom of the network have been found.

The IMPACTS module has been designed to study the impacts of the electric and non-electric systems separately or together. It can receive data from the BALANCE, but direct user input is also possible.

IMPACTS computes the following variables:

- Air - quantity of pollutants emitted
- Water - water input requirements, waste water discharge quantity, quantity of pollutants discharged

— Land - quantity of land used
— Solid Waste - quantity of waste generated
— Occupational Health and Safety - rates of illness, injury, fatalities
— Resources - labor and materials required.

These burdens are computed with and without the imposition of environmental controls. The incremental cost of environmental control is also computed.

3. Results

The Hungarian Power Companies commissioned the SYSTEMEXPERT Consulting Ltd to test and compare the above mentioned models for Hungarian data. Experts of the Power Companies prefer the use of ENPEP. On one hand they prefer scenario analyzing models, since they consider only some long term scenarios to be feasible in advance, and they may not accept the results of such an optimization model like the EFOM_ENV. On the other hand, some of their experts already have experience in using the WASP model, whose structure is similar to the modules of ENPEP, and its results can automatically be transferred to the IMPACTS module of ENPEP. Following, we outline the results of the BALANCE-IMPACTS run.

Three scenarios which contain different investment schedules of new power plants have been examined by the BALANCE. Scenario 'A' is a lignite-nuclear combination. According to this scenario a lignite power plant is built first and a nuclear one second. Finally, a hard coal fired plant is built. There is no new hydrocarbon fired plant. Scenario 'B' is based on use of hydrocarbon fuels. The lignite fired, the nuclear, and the hard coal fired plants may enter the system later than in scenario 'A'. New oil and gas fired plants are allowed. Scenario 'C' is a lignite-hard coal combination. According to this scenario, a nuclear power plant would be built only in 2010, while the hard coal fired plant may enter the system after 2004.

The following groups were distinguished in the Hungarian power plant system:

- Existing lignite fired power plants,
- New lignite fired power plants,
- Existing brown coal fired power plants,
- New brown coal fired power plants,
- Existing black coal fired power plants,
- New black coal fired power plants,
- Existing oil and gas fired power plants,
- Existing hydrocarbon and inert gas fired power plants,
- New oil and gas fired power plants,
- Existing gas turbines,

- New gas turbines on fuel oil,
- New gas turbines on gas,
- Nuclear power plants,
- Hydroelectric power stations.

Tables 2–4 show the emissions of five pollutants for the different scenarios. Similar emission levels can be reached by 2010 according to scenario A and C. Emissions are lower in scenario B, where oil and gas plants of high variable costs are preferred. In all scenarios a new nuclear plant is considered to enter the system. This means that share of nuclear plants in the electricity production will soon exceed 50%. Even the other model runs showed that increase of nuclear capacity is inevitable, if emission limits regulated by international contracts to be met.

References

CMDI, 1992: *Adaptation of Models for the Determination of Abatement Strategies* (ed.: *S. Molnár*) (in Hungarian). Working paper, Central Mining Development Institute, Budapest.

Systemexpert, 1994a: *Use of Energetical Models Which Can Take into Account the Environmental Impacts* (ed.: *S. Molnár*) (in Hungarian). Working paper, Systemexpert Consulting Ltd, Budapest, Hungary.

Systemexpert, 1994b: *Investigation of the New Energy Strategy of the Hungarian Power Companies Ltd by the Model EFOM_ENV* (ed.: *S. Molnár*) (in Hungarian). Working paper, Systemexpert Consulting Ltd, Budapest, Hungary.

Systemexpert, 1995a: *Analysis of the Newest Energy Strategy of the Hungarian Power Companies by the Model EFOM_ENV* (in Hungarian). Systemexpert Consulting Ltd, Budapest, Hungary.

Systemexpert, 1995b: *Environmental Evaluation of Energy Strategies of the Hungarian Power Companies by the Model BALANCE-IMPACTS* (in Hungarian). Systemexpert Consulting Ltd, Budapest, Hungary.

Table 2. Air pollution emissions (1000 kg/year) in Hungary

Balance – Impacts Case A

Year	Mode	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
PART	uncontr.	19135.6	17724.9	17547.2	11904.9	12368.9	13177.0	13383.4	6559.9	5105.8	4644.0
	contr.	19135.6	17724.9	12731.8	8225.0	8769.7	10161.7	11281.3	5053.0	3726.4	3405.1
	reduct. %	0.0	0.0	27.4	30.9	29.1	22.9	15.7	23.0	27.0	26.7
SO_2	uncontr.	410452.9	380989.0	369060.6	251609.1	252962.3	264450.5	262865.9	120967.2	89773.8	80775.8
	contr.	410452.9	380989.0	114564.3	70055.2	76514.8	94484.1	109163.9	64760.9	60690.5	54738.9
	reduct. %	0.0	0.0	69.0	72.2	69.8	64.3	58.5	46.5	32.4	32.2
NO_X	uncontr.	23252.2	21730.2	25032.4	16260.7	18779.2	22220.8	24930.9	15904.4	14810.1	13651.9
	contr.	23252.2	21730.2	15415.1	10812.1	13092.8	14390.4	15185.8	10277.7	9300.7	8763.9
	reduct. %	0.0	0.0	38.4	33.5	30.3	35.2	39.1	35.4	37.2	35.8
CO	uncontr.	16954.0	15021.8	14015.8	10588.3	13422.8	13550.1	13113.7	9731.4	8673.2	8319.1
	contr.	16954.0	15021.8	9604.0	7219.8	10124.8	10840.0	11298.5	8416.3	7476.7	7250.2
	reduct. %	0.0	0.0	31.5	31.8	24.6	20.0	13.8	13.5	13.8	12.9
CO_2^*	uncontr.	15876.5	14904.6	15958.5	11047.2	13940.3	15450.8	16473.2	11159.7	10015.1	9464.0
	contr.	15876.5	14904.6	15207.0	10474.1	13378.4	15000.1	16186.9	10949.2	9825.3	9295.7
	reduct. %	0.0	0.0	4.7	5.2	4.0	2.9	1.7	1.9	1.9	1.8

* in kilotonnes

Table 3. Air pollution emissions (1000 kg/year) in Hungary

Balance – Impacts Case B

Year	Mode	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
PART	uncontr.	19135.6	17724.9	17547.2	12490.0	14615.4	14248.8	12618.4	5477.0	4022.2	3560.4
	contr.	19135.6	17724.9	12731.8	8586.6	10217.9	10913.2	10516.2	3970.1	2642.8	2321.5
	reduct. %	0.0	0.0	27.4	31.3	30.1	23.4	16.7	27.5	34.3	34.8
SO_2	uncontr.	410452.9	380989.0	369060.6	265587.9	306967.3	293673.3	256675.8	111457.0	80257.2	71259.2
	contr.	410452.9	380989.0	114564.3	75809.3	100181.5	110301.6	102973.8	55250.7	51173.9	45222.3
	reduct. %	0.0	0.0	69.0	71.5	67.4	62.4	59.9	50.4	36.2	36.5
NO_X	uncontr.	23252.2	21730.2	25032.4	17030.0	21725.3	23495.2	21905.4	11625.0	10528.3	9370.1
	contr.	23252.2	21730.2	15415.1	10880.4	13126.5	13393.1	12160.3	5998.3	5018.9	4482.1
	reduct. %	0.0	0.0	38.4	36.1	39.6	43.0	44.5	48.4	52.3	52.2
CO	uncontr.	16954.0	15021.8	14015.8	10265.4	11827.3	10947.5	9218.8	4264.8	3203.5	2849.4
	contr.	16954.0	15021.8	9604.0	6697.1	7802.5	7953.8	7403.6	2949.6	2007.1	1780.5
	reduct. %	0.0	0.0	31.5	34.8	34.0	27.4	19.7	30.8	37.4	37.5
CO_2^*	uncontr.	15876.5	14904.6	15958.5	10961.1	13424.0	13879.0	12717.4	5779.1	4631.5	4080.4
	contr.	15876.5	14904.6	15207.0	10354.9	12739.3	13382.0	12431.1	5568.7	4441.6	3912.0
	reduct. %	0.0	0.0	4.7	5.5	5.1	3.6	2.3	3.6	4.1	4.1

* in kilotonnes

Table 4. Air pollution emissions (1000 kg/year)

Balance – Impacts Case C

Year	Mode	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
PART	uncontr.	19135.6	17724.9	17547.2	12433.3	12887.1	13737.3	10868.5	6825.8	5302.1	4662.1
	contr.	19135.6	17724.9	12731.8	8753.5	9287.9	10722.0	9172.1	5301.5	3883.0	3423.1
	reduct. %	0.0	0.0	27.4	29.6	27.9	22.0	15.6	22.3	26.8	26.6
SO_2	uncontr.	410452.9	380989.0	369060.6	255836.6	257107.9	268933.1	208135.6	124065.1	92061.3	80141.9
	contr.	410452.9	380989.0	114564.3	74282.7	80660.5	98966.7	81451.7	66847.3	62135.0	54105.0
	reduct. %	0.0	0.0	69.0	71.0	68.6	63.2	60.9	46.1	32.5	32.5
NO_X	uncontr.	23252.2	21730.2	25032.4	18713.1	21200.8	24768.8	20937.8	17152.9	15841.0	14152.1
	contr.	23252.2	21730.2	15415.1	13264.5	15514.5	16938.5	14411.8	11312.4	10151.1	9264.1
	reduct. %	0.0	0.0	38.4	29.1	26.8	31.6	31.2	34.1	35.9	34.5
CO	uncontr.	16954.0	15021.8	14015.8	14135.0	16934.1	17207.4	14528.4	11372.1	10105.9	9388.0
	contr.	16954.0	15021.8	9604.0	10766.6	13636.1	14497.4	13049.3	10043.7	8874.6	8319.2
	reduct. %	0.0	0.0	31.5	23.8	19.5	15.8	10.2	11.7	12.2	11.4
CO_2*	uncontr.	15876.5	14904.6	15958.5	13795.1	16635.0	18733.8	15733.8	11943.0	10538.7	9586.3
	contr.	15876.5	14904.6	15207.0	13222.0	16073.1	17913.7	15497.3	11730.9	10343.3	9418.0
	reduct. %	0.0	0.0	4.7	4.2	3.4	2.5	1.5	1.8	1.9	1.8

* in kilotonnes

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

A Policy Analysis Approach to Analysis of Climate Change Response Policies

F. R. Rijsberman

Managing Director, Resource Analysis,
Zuiderstraat 110, 2611 SJ Delft, The Netherlands

Abstract—For the development of socially acceptable climate change response policies it will be necessary to analyze the consequences of the alternative response policies for all stakeholders involved. Based on such an analysis a dialogue can be opened with the stakeholders or their representatives. It will be necessary to communicate, and negotiate, with various government agencies as well as other organizations concerned with fulfilling their commitments to reduce emissions.

Many of the Country Studies (CSs) that are currently being undertaken have a component that involves the development of a modeling framework that allows identification of GHG abatement strategies, or response policies, and their costs. It is argued in this paper that this is a necessary but not sufficient condition for the development of acceptable response policies. In addition to aggregated costs at the national level, other criteria have to be taken into account, such as the distribution of costs over stakeholders, the political feasibility of policy measures, financial feasibility, or social acceptability.

This paper proposes a policy analysis approach to: (a) expand the cost-effectiveness undertaken in CSs with the equity criteria, and (b) develop decision support tools that can be used directly by decisionmakers, allowing input of their (qualitative expertise), judgement and values, and can serve as tools for communication and negotiation among stakeholders.

Key-words: climate change, response policies, equity criteria, decision support.

1. Introduction

The work for the national communications to the UNFCCC has, for most countries, focused on emissions inventories. The national communications have also listed measures to reduce greenhouse gas emissions, but to date there has not been much analysis, generally speaking, of the relative desirability of these measures from the perspective of different stakeholders, or impacted groups. For the coherent development of socially acceptable climate change response policies it will be necessary to analyze the consequences of the alternative response policies for all stakeholders involved. Based on such an analysis a dialogue can be opened with the stakeholders or their representatives. It will be necessary to communicate, and negotiate, with various government agencies as well as other organized interests (for example, ministries of agriculture, transport, and industry, and the business community and NGOs) to obtain their commitments to reduce emissions.

Many of the Country Studies (CSs) that are currently being undertaken have a component that involves the development of a modeling framework that allows identification of GHG abatement strategies, or response policies, and their costs. It is argued in this paper that this is a necessary but not sufficient condition for the development of acceptable response policies. In addition to aggregated costs at the national level, other criteria have to be taken into account, such as the distribution of costs over stakeholders[1], the political feasibility of policy measures, financial feasibility, and social acceptability.

The different sectors of the economy that generate greenhouse gas emissions can be looked at as stakeholders with conflicting interests in the issue of greenhouse gas emissions reduction. The sectors will have to bear the cost of emissions reductions and will naturally attempt to limit their contribution. The agency responsible for development of a climate policy could be looked upon as an honest broker, with the objective of reaching an overall goal of emissions reduction with the cooperation of all partners. The national climate policy will, generally speaking, be the outcome of a decisionmaking process that sets emissions reduction targets for the various stakeholders (for example, contributions from the energy sector, transportation, agriculture, wastes, and so forth).

In the decisionmaking process, there are many arguments or criteria on which the final decision can be based. *Ridgley* and *Rijsberman* (1994) have distinguished three types of criteria that play a role in the selection of the most desirable alternative — the national climate policy — related to effectiveness, equity, and efficiency. In the decisionmaking or negotiation process such arguments may be made explicit or left implicit. Ridgley and Rijsberman argue that policies are often based on a confusing, implicit mixture of effectiveness, equity, and efficiency arguments. They propose an approach in which these three groups of arguments are made explicit and treated separately. This involves effectiveness arguments in setting an overall target for the level at which GHG concentrations ought to be stabilized and in negotiating fair shares of the allowable global emissions for regions and nations based on equity arguments. *Ridgley* and *Rijsberman* (1994) describe a negotiation-based approach to develop equity targets based on a set of equity principles related to culpability as well as ability to pay. Finally, within the framework of national and regional accountability, the most efficient way can be found to achieve a

[1] The costs referred to here can be expressed in terms of expenditures, or reduced income, by groups such as households, or in terms of other measures such as changes in employment.

target through cost-effectiveness analysis, but will also require further negotiation to allocate emissions, or emission reductions, to the stakeholders.

This paper presents a policy analysis approach to the analysis of climate change response policies that includes cost-effectiveness analysis as well as equity considerations with respect to impacted groups. Such an approach can be used as a basis to communicate, and negotiate, with the stakeholders involved to achieve an acceptable policy.

2. *Policy Analysis and Climate Change*

Policy analysis can be defined simply as a systematic process for solving a policy problem by identifying, analyzing, and evaluating alternative options. Although not a necessary requirement, the analysis is usually characterized by having a group make decisions based on conflicting interests and multiple criteria. The advantages of a policy analysis approach are that it structures the analysis of complex problems and makes decisionmaking in uncertain circumstances more transparent and reproducible. Many Country Studies employ some form of policy analysis, although often in the somewhat limited form of a cost-effectiveness analysis. The approach is discussed, using as an example the problem of developing a socially acceptable climate policy.

The first issue is to set out clearly what the objective of the analysis is. This usually requires much more thought and discussion than expected at the outset of the analysis. For developing a socially acceptable climate policy the objective could, for example, be formulated as follows: achieving such national greenhouse gas emission targets that are realistic, affordable, and widely acceptable to stakeholders and that can be adapted flexibly to a wide range of economic development scenarios.

Such a formulation makes explicit not only the achievement of the target, but also other arguments such as feasibility, affordability, and acceptability of a policy, and, as well, the issue of uncertainty in economic development. Other arguments could, no doubt, be added. In fact, for each aspect sub-objectives could be formulated that express more precisely the concerns of the stakeholders.

Eventually, alternative options for climate policies will have to be judged or evaluated for their degree of conformity to the overall objective or set of sub-objectives. This is normally done through the definition of a number of criteria that are used as yardsticks to measure how a certain policy scores with respect to a certain part of the overall objective or a specific subjective. Some of the criteria may represent variables that can be quantified and measured or modelled; others may only be evaluated in qualitative but no less relevant terms. Possible criteria that could be used for the above formulated objective could be the following set:

- National equivalent carbon dioxide emissions (tons/year)
- Realism (scored qualitatively, based on legal analysis, for instance)
- Separable costs of emissions reductions (monetary units)
- Distribution of costs over stakeholders
- Social acceptability
- Sensitivity to changes in economic development scenarios
- Contributions of sectors to the overall reduction target (percent).

An important characteristic of policy analysis is that it must deal with uncertainties in a consistent and coherent manner. This is normally done by defining *scenarios* — sets of assumptions with respect to uncertain future developments or situations that affect the functioning of the system under consideration are not determined or controlled within the system, but have a significant impact on the evaluation of the policy alternatives. Scenarios, then, are seen as separate from response policies, that is, sets of measures under the control of the decisionmakers. This case includes the following candidate scenario variables:

- The national target for greenhouse gas emissions (unlikely to be fixed permanently within the near future)
- The rate of economic development
- The autonomous (without climate policy) change in emissions factors per unit of economic production over time.

A *measure*, in policy analysis terms, is a single, specific action that ranges, for the purposes of climate change, from carbon taxes to awareness-raising campaigns. A complete, consistent, integrated set of measures to achieve the overall goal is defined as a *strategy* or a *policy*.

The sequence of steps in a typical policy analysis can be outlined as follows (although the actual analysis will often be carried out in a several of iterations):

- Definition of the problem, objective, criteria, and analysis conditions (for example, scenario variables and assumptions, base year and target years, system boundaries, system components);
- Analysis of the system components, establishment of a database (for example, emissions inventory in the base year and an emissions forecast for the target year for different economic development scenarios);
- Development of tools to analyze the consequences of alternative strategies (for example, a modeling framework);
- Identification and formulation of alternative strategies or response policies;
- Analysis of strategies, using the modeling framework, in order to assess the scores of each of the alternatives for each of the criteria;
- Evaluation of the relative desirability of the alternatives for the stakeholders and negotiation of the most desirable and socially acceptable alternative.

3. Development of a Decision Support Tool

The response policy components of Country Studies often undertake some form of the analysis outlined above, but focus largely on economic efficiency criteria. This can also be described as cost-effectiveness analysis. This is described, for instance, in the presentation by *Gaj* (1995) of the Polish Country Study. The final product of such an analysis is a set of response policies and associated economic impacts.

It is argued here that such analyses should explicitly incorporate the other concerns of stakeholders, as referred to above, and should also explicitly address the negotiation process among stakeholders. To this end, it is proposed that decision-support tools be developed with the following characteristics:

- The decision-support tools should be usable directly by decisionmakers (stakeholders or their representatives) without having scientists or analysts as intermediaries.
- The tools should be user friendly, attractive, and interactive. That is, they should allow the decisonmakers to understand the structure and characteristics of the response policies and to input and see the consequences of their or own preferences or judgements.
- The tool can be thought of as a post-processor of the results of the technological-economic modeling framework as described by *Gaj* (1995). For the decision support tool proposed here, the resulting set of response policies and associated economic impacts could be input.
- Impacts or scores of the response policies for other (noneconomic) criteria can be determined based on additional modeling, expert (qualitative) judgement, or directly put in by the decisionmakers.
- A second major input from the decisionmakers are the relative weights of the criteria, which will vary depending on the perspective (interests) of the stakeholders. To this end, the tool should accommodate one or more multicriteria analysis supports or techniques (ranging from simple coloured scorecards to formal analysis techniques).
- The tool should, at the least, be structured so as to invite and enable discussion among decisionmakers using the tool. It should stimulate the exchange of opinions and could also incorporate formal negotiation procedures, such as those proposed by *Ridgley* and *Rijsberman* (1994).

A number of models have been developed with the objective of integrating the climate system, global biogeochemical cycles, and human-societal components. Such integrated models have been used in the international work of IPCC and INC for climate change issues. Examples include the IMAGE model (*Rotmans*, 1991; *Alcamo*, 1994), and the preparation of the Convention on Long Range Transboundary Air Pollution for acid rain issues, that is, the RAINS model (*Hordijk,* 1991), as discussed by *Swart* (1994, Chapter 3). These models are, generally speaking, research tools built to be operated and interpreted by scientists rather than decisionmakers. Although their results may well be used to support decisionmaking, or even negotiation processes, they are not the decision support tools that can be used directly by decisionmakers as described above. *Swart* (1994) concludes, for instance, that to gain acceptability, the IMAGE model had to be redeveloped in a user friendly FORTRAN-based version, because the original model had few and unattractive graphics, and was written in a less accessible simulation language (ACSL).

User friendly, interactive decision-support tools that satisfy the six conditions above have been developed recently for related climate issues, that is, the analysis of policies responding to sea level rise. For the World Coast Conference 1993, hosted by The Netherlands Government in Noordwijk in November 1993, a group of about 300 high-level decisionmakers, with various sectoral backgrounds, NGO and representatives, successfully used decision-support tools that were developed for the occasion. One of these tools, COSMO, focuses on the preparation and analysis of sea level rise adaptation policies in the context of integrated coastal zone management (*Resource Analysis*, 1994). A second model, CORONA, uses a computer-based role-play to focus on the institutional requirements for implementing coastal zone management plans (*Rijsberman et al.*, 1995).

COSMO and CORONA are based on a fictitious area and were developed[2] as awareness-raising tools and as ways to improve communication among stakeholders. Following their successful application at the World Coast Conference, the models have been used around the world as training tools at workshops and seminars on integrated coastal zone management, and climate change and sea level rise problems. Also, as a consequence, a family of evolving decision-support tools is being developed by Resource Analysis with increasingly practical and realistic applications, such as the following:

- A decision-support tool, SAMPAK, to prepare coastal zone management strategies for the Pak Phenang area in Southern Thailand[3] has been used for international training seminars and is currently being considered as a study tool to analyze the operation of a new water-resources dam in the area.
- A prototype decision-support system, WESTOOL, for managing the Western Scheldt Estuary between Belgium[4] and The Netherlands will be

---

[2] Developed by Resource Analysis in cooperation with the CZM Centre of the National Institute for Coastal and Marine Management in The Netherlands.

[3] Developed by Resource Analysis, in cooperation with the Coastal Resources Institute (CORIN) of the Prince of Songkla University, Hat Yai, Thailand, and supported by The Netherlands Ministry for Foreign Affairs.

[4] Developed by Resource Analysis in cooperation with the Ministry for Transport, Public Works, and Water Management, with support of the national research programme on Land-Water-Information technology.

implemented as part of a national research program in The Netherlands in the coming years.

- A decision-support tool, COMA[5], will be used to analyze the impact of population growth, economic development, and coastal zone management policies on the coastal system of West Africa from Senegal to Nigeria.
- A decision-support tool, CORAL, to analyze cost-effective policies to manage and protect coral reef ecosystems[6].

4. Conclusions

The development of socially acceptable climate change response policies will require not only cost-effectiveness analysis of mitigation and adaptation options, but will have to include impacts on equity such as the distribution of costs and benefits over social groups.

The negotiation process among stakeholders to achieve socially acceptable response policies can be aided by the development of user friendly, interactive decision-support tools.

References

Alcamo, J. (ed.), 1994: *IMAGE 2.0: Integrated Modeling of Global Climate Change*. Kluwer Academic Publishers, Dordrecht (reprinted from *Water, Air, and Soil Pollution, Vol.* 76, 1-2, 1994).

Gaj, H., 1995: Modeling impacts of measures. Paper presented at the Central and Eastern European Workshop on Greenhouse Gas Emission Inventories and Response Policies, Budapest, May 8-11, 1995.

Hordijk, L., 1991: *An Integrated Assessment Model for Acid Deposition in Europe*. Dissertation, Free University of Amsterdam.

Resource Analysis, 1994: *Coastal Zone Simulation Model (COSMO) Manual*. Resource Analysis, Delft, and CZM Centre, National Institute for Coastal and Marine Management, The Hague.

Ridgley, M.A. and *Rijsberman, F.R.*, 1994: *Setting Targets for Climate Policy: An Approach to Develop Equity Targets*. Report prepared for The Netherlands Ministry of Housing, Physical Planning and the Environment (VROM). Resource Analysis, Delft.

Rijsberman, F.R., Westmacott, R.S., and *Waardenburg, D.,* 1995: *CORONA: Coastal Resources Management Roleplay: Trainers' Manual*. Resource Analysis, Delft.

Rotmans, J., 1991: *An Integrated Model to Assess the Greenhouse Effect*. Kluwer Academic Publishers, Dordrecht.

Swart, R., 1994: *Climate Change: Managing the Risks*. Dissertation, Free University of Amsterdam.

---

[5] Developed by Resource Analysis in cooperation with the World Bank, Division for Environmentally Sustainable Development in Africa (AFTES), and the Land, Water and Natural Habitats Division (ENVLW).

[6] Being developed by Resource Analysis in cooperation with an international team of scientists for the World Bank, Latin American and Caribbean Environment Division (LA3EU).

IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 99, No. 3–4, July–December 1995

A Mixed Bag: Instruments for CO_2-Emission Abatement in The Netherlands

W. J. Iestra and **M. Bonney**

Ministry of Housing, Spatial Planning and Environment,
P.O. Box 30945, 2500 GX Den Haag, The Netherlands

Abstract—The 'mixed bag' referred to in the title of this paper is a mixed bag of policy instruments that can be used to encourage or compel energy conservation and reduction of CO_2 emissions. The instruments contained in the mixed bag must be tailor-made for the situations in which they are applied. Differences in the nature and size of the target groups being addressed must be taken into account in deciding which policy instrument should be applied. The choice as to the type of instrument and the degree to which it is implemented is also influenced by the policy objective being pursued. This fine tuning of policy instruments to situation-specific circumstances improves both the effectiveness and efficiency of policy efforts. This is important if we want to maximize results within the constraints of the 'No Regrets' approach.

Another important characteristic of the mixed bag is that it is a cohesive whole. The instruments it contains reinforce and complement one another in such a way that the effect of the whole is more than the sum of the parts.

This paper begins with a sketch of the development of climate change policy in The Netherlands. The paper then focuses on four innovative policy instruments that are elements of the mixed bag: agreements with branches of industry, energy-related requirements in environmental permits and general administrative orders, structured activities on the part of energy distribution companies, and energy taxes.

Key-words: climate change, No Regrets, policy instruments, target groups, voluntary agreements, environmental permits, energy taxes.

1. Development of Climate Change Policy in The Netherlands

The roots of Dutch climate change policies can be found in the first National Environmental Policy Plan (NMP), issued in 1989. The Government set a target of stabilizing CO_2 emissions in The Netherlands at their 1989–1990 level in the year 2000. Shortly thereafter, during the formation of a new national government, a political commitment was made to an even farther reaching CO_2 target.

This new target — set down in the National Environmental Policy Plan Plus (NMP-Plus) and sent to Parliament in 1990 — is to reduce CO_2 emissions by 3 to 5 percent in 2000 relative to 1989–1990.

In 1990, when the new target was adopted, it appeared likely that the target could be achieved with the traditional instruments of energy conservation policy (along with contributions from the transport and waste sectors, as well as some fuel switching). The measures to be taken were set out in the first Memorandum on Energy Conservation (NEB) in 1990. Projections of energy price development made at that time assumed a continuing rise in world oil prices throughout the 1990s, growing by 65 percent in real guilders between 1990 and 2000. Prices at this level would have boosted the effectiveness of such traditional policy instruments as subsidies, standards for insulation and appliance energy consumption, research and development, and public education and awareness building. Given this expectation about rising prices, the Government was reasonably confident that the package of measures announced in the NMP-Plus and the NEB would be sufficient to reach the goal of reducing CO_2 emissions by 3 to 5 percent. However, just to be on the safe side, the Government also began to prepare for the eventuality that the then-existing package of measures might prove to be inadequate for attaining the 3 to 5 percent reduction, or that more far-reaching targets might be agreed to at the intergovernmental level. These preparations took the form of research into the possibilities of deploying regulatory instruments geared to decreasing CO_2 emissions (such as making use of the environmental permitting system or issuing general administrative orders) and the possibilities of imposing regulatory charges on energy use.

During the five years that have passed since the NMP-Plus was issued, our perception of energy price development has changed radically. Where in 1989 our forecasts assumed that real-world oil prices would rise substantially during the 1990s, we now find ourselves with world oil prices at much lower levels than in the early 1970s. Recent official projections made for policy-development purposes in The Netherlands assume that real energy prices will remain more or less constant between 1995 and 2000 and that economic growth will be modest. Under these conditions, application of existing policy instruments will have to be intensified and additional policy instruments will have to be deployed in order to attain even the 3 percent emission reduction target for CO_2.

In December 1993, the Government issued the second National Environmental Policy Plan (NMP 2) and the second Memorandum on Energy Conservation (VNEB), indicating, among other things, how policy efforts in the area of climate change were to be enhanced. Targets for energy-efficiency improvements were set for different sectors, including households (23 percent), non-residential buildings (23 percent), industry (19 percent), agriculture (26 percent), transport (10 percent), and power stations (26 percent). The overall efficiency improvement (including renewables) will lead to energy consumption of 2,865 PJ in 2000 (550 PJ less than what it would have been without the policy measures; slightly more than what it was in 1990). Energy efficiency (including renewables) will be responsible for roughly two thirds of the CO_2 reduction needed, with the remainder coming from transport, recycling, reduced coal use, afforestation, and structural changes. This paper addresses only the energy-efficiency measures.

The measures being taken to ensure that the various sectors meet their targets include such things as retrofit insulation of houses and other buildings; energy-efficiency standards for appliances such as washing machines, central heating boilers, pumps, and fans; subsidies for investments in energy conservation; accelerated depreciation of investments in innovative technologies; and tightening the insulation standards for new houses and other buildings. The instruments being deployed in order to implement these measures are then largely the traditional ones of energy conservation policy: subsidies, standards for insulation and appliance energy consumption, research and development, and public education and awareness.

The following table provides an overview of the target groups addressed in this paper:

Table 1. Target groups of energy conservation policy

	Number	Share in energy consumption*
Households	6,000,000	28%
Non-residential buildings	535,000	16%
Other small businesses	45,000	7 %
Greenhouse horticulture	15,000	8 %
Light industry	44,000	21 %
Heavy industry	65	20 %

* transport and feedstocks excluded

The following four sections of this paper describe the Dutch experience to date with each of the instruments contained in the mixed bag, discuss their strengths and weaknesses, and suggest conditions that are pre-requisite to their use.

2. Agreements With Branches of Industry

Agreements with branches of industry are one of the most important elements in the mixed bag of energy conservation policy instruments being utilized by the Dutch government.

Dutch manufacturing industry consists of about 20,000 companies and accounts for more than 40 percent of total domestic energy consumption in The Netherlands. The target adopted for the manufacturing industry as a whole is to improve its energy efficiency (excluding its use of feedstocks) by 19 percent by the year 2000.

The Dutch government has currently signed agreements with 22 branches of industry (such as iron and steel, chemicals, glass, cement, textiles, sand-lime bricks, and so forth) and with the greenhouse horticulture sector and is engaged in discussions with 9 others with the aim of arriving at agreements as to how this target will be met. These sectors account for about 80 percent of the energy used by the manufacturing industries. In principle this system of voluntary agreements can also be used with nonindustrial sectors such as bakeries, hotels, restaurants, and cafes.

Why voluntary agreements? The idea behind this approach is that companies must acknowledge and act on their responsibility to contribute to sustainable development. It is part of the overall 'target group approach' to environmental policy adopted by the Dutch government. The target group approach rests on the twin notions of internalizing environmental considerations in decision-making and public-private partnership in finding and implementing solutions to environmental problems. These voluntary agreements allow the companies themselves to determine what actions they will undertake in order to achieve the target. When they sign the agreement, they commit themselves to taking those actions. The government, for its part, commits itself to creating the conditions necessary for the companies to fulfil their obligations—conditions having to do with financing, investment climate, provision of information, technical assistance, and so forth. It is a two-way street, a form of self-regulation in which the Government's role is defined by support rather than by intervention. The private-sector commitment is met with public-sector commitment.

The process by which agreement is reached with a branch of industry begins with a period of study. The Netherlands Agency for Energy and Environment (Novem), an intermediary organization that prepares the agreements on behalf of the Ministry of Economic Affairs, discusses possibilities for energy-efficiency measures with the industrial branch organization. This discussion increases the industry's awareness of its potential for improving the efficiency with which it uses energy. An in-depth study (lasting 6–12 months) of ways to increase energy efficiency is carried out, preceded by a declaration of intent, in which the industry states its intention to undertake (further) energy savings measures. If the in-depth study clearly shows that the measures proposed constitute a sufficient and measurable improvement in energy efficiency, then the agreement can be signed.

Because the agreement is a public document, it contains only general information about the specific measures to be implemented. Where necessary, detailed information about individual companies is included in separate confidential agreements (annexes) concluded between the individual companies and Novem. The degree to which individual companies contribute to the overall effort can differ depending on their specific circumstances.

Important provisions of the agreements include first of all the target, which is fixed on the basis of the in-depth study of potential. An intermediate target for the year 1995 is included along with the target for the year 2000. The targets vary for each sector, but are mostly in the region of 20 percent by the year 2000. The measures to be taken by both the industry involved and the Ministry are also set down in the agreement. However, the agreements do not only list the measures that will be taken. They also—and perhaps even more importantly—contain provisions relating to the monitoring and reporting of activities. These provisions are absolutely essential. They make it possible to monitor progress and, where necessary, adjust activities in order to ensure that the targets are being met. This adjustment process is facilitated by elements in the agreement that provide for regular consultations between the parties involved. There are also provisions relating to how the agreement may be altered or terminated.

Voluntary agreements as utilized in The Netherlands are based on thorough investigations of the possibilities for energy-efficiency measures and provide for a flexible approach adjusted to the needs of the industrial branches. This flexibility is one of their greatest strengths as an instrument of policy. Another of their strengths can be found in the interactive process by which they are drawn up: the studies, surveys, consultations, and so forth that generate a great deal of information about the potential for saving energy in the sector involved. This process raises awareness of energy conservation options in both the industry involved and the Government.

One of the most often mentioned weaknesses of the voluntary agreements is simply the fact that their status under the law is still open to interpretation. There are no sanctions for failure to live up to the commitments made, and, therefore, uncertainty exists about whether the targets will be achieved. Another frequently heard criticism is that unlike market-oriented instruments, agreements do not necessarily result in measures that minimize the total costs of achieving a given environmental objective. While this observation is generally true, it is probably not really relevant in a No Regrets policy context where, by definition, the measures taken serve more than one policy objective and where costs are usually not high.

The instrument of voluntary agreements can only be used efficiently when the sector involved is well organized and has designated a spokesperson to carry out the consultations and negotiations with the representative of the government. Because this approach is based on consensus seeking and consultation, it can be a labour-intensive process. Negotiating individually with each of the companies in the sector would be prohibitively time consuming. It is also necessary to build into the agreement good provisions for monitoring compliance and for adjusting to changing circumstances. Without good monitoring and review provisions the agreements lose much of the flexibility and dynamic that are two of their greatest strengths.

3. Energy-Related Requirements in Environmental Permits and General Administrative Orders

Regulation in the form of permits or general administrative orders provides the possibility for reinforcing, or supplementing, voluntary agreements.

The (new) Environmental Protection Act in The Netherlands empowers the permitting authorities to set requirements relating to the rational use of energy and raw materials in environmental permits and makes it possible for the central government to issue general administrative orders setting such requirements for categories of establishments. This provision of the Act entered into force as of March 1993. In the meantime, provisions have been made to deal with the relationship between individual permits and voluntary agreements and the role of the central government in this respect.

Voluntary agreements between the Ministry of Economic Affairs and the sector organization set the target for energy-efficiency improvement and the financial support for research and development, energy management, information, and training. The companies themselves determine the concrete steps to be taken to meet the target and set them out in corporate energy plans. Provisions in the Environmental Management Act, which entered into force in early 1993, require the permitting authorities to consider whether the environmental permit granted to an installation should include requirements regarding energy use. Once this provision went into effect there was clearly a potential for conflict between the voluntary approach and the regulatory approach of the environmental statute. In order to prevent possible conflicts between the voluntary agreements on the one hand, and the environmental permits on the other, the permitting authorities have been advised as to how they can take the voluntary agreements into account when granting permits. It was agreed that The Netherlands Agency for Energy and Environment (Novem) would evaluate each corporate energy plan and submit a report to the permitting authority. If Novem concludes that the company is meeting its commitments under the voluntary agreement, then the permitting authority is advised to limit energy-related provisions in the permit to a reporting requirement. If Novem concludes that the company is not meeting its commitments under the agreement, then the permitting authority is advised to follow a different, more stringent procedure to determine whether energy-related prescriptions (technology standards, performance standards, or a combination) should be included in the permit. This advice to the permitting authorities made it possible to preserve the strengths of both approaches (the voluntary and the regulatory), while at the same time compensating for their individual weaknesses.

The fact that permits are available to governmental authorities as an instrument of policy makes it impossible for companies to take a 'free ride' on the voluntary agreements. The existence of the regulatory instrument ensures that all companies are dealt with on equal terms and prevents companies from refusing to participate out of fear that their competitors will refuse to participate.

The strengths and weaknesses of this policy instrument are by and large the mirror images of the strengths and weaknesses of the voluntary agreements. While flexibility is a strength of the agreements, it is a weakness of the permits that they are less flexible (although they can be revised where circumstances warrant). While it is a weakness of the agreements that they do not offer certainty, it is a strength of the permits that they do. Another strength of permits is that the procedures by which they are drawn up and issued are grounded in legislation. Third parties have access to the process and there are formal channels for having their views heard and considered.

Combining these two instruments allows policy makers to take advantage of their strengths, while mitigating their individual weaknesses. The agreements will be especially important in a transition period, because it will likely take several years before permits actually contain energy-related provisions on a large scale.

4. Activities of the Energy Distribution Sector

The energy distribution sector consists of the companies that distribute gas and electricity to industrial, commercial, governmental, and residential customers. This sector has a statutory responsibility to promote efficient energy consumption in The Netherlands. It has accepted the challenge of contributing to a cleaner environment, notably with regard to reductions in emissions of greenhouse gases and acidifying gases. In order to meet this challenge, the energy distribution sector has drawn up a collective plan of action (the Environmental Action Plan, or MAP) that focuses on energy saving (their target is 10-percent savings in energy supplied by the distribution sector in the year 2000) and alternative methods of power generation. In addition to this collective plan, 52 (individual or joint) environmental action plans have been drawn up by the 68 companies that are members of the branch organization. These individual plans have the backing of the shareholders and cover more than 90 percent of the energy sales by the sector.

What is in the environmental action plan? The collective plan, drawn up in consultation with the central government, contains the measures proposed for the different target groups. Three target groups are differentiated: households, business and government, and the energy-distribution companies themselves. The collective plan also describes how the measures are being implemented and contains information regarding the scheduling and financing of the measures.

The measures contained in the environmental action plan are aimed at improving the penetration of the following technologies:

- Energy-efficient lighting,
- Insulation,
- High-efficiency water and space heating,
- Co-generation,
- Wind energy.

The distribution companies, collectively and individually, are undertaking the following four kinds of activities in executing the plan:

- Furnishing their customers with information and advice about possibilities for saving energy;
- Providing prior financing and leasing arrangements for their customers who want to acquire energy-efficient equipment;
- Administering subsidy schemes and incentive arrangements for such things as insulation and high-efficiency boilers in homes, energy-saving light bulbs in homes, and large-scale energy-efficient lighting projects in non-residential buildings;
- Stimulating investments in additional wind-power facilities and co-generation, with financial support from the central government.

The funding needed to carry out the environmental action plan is provided jointly by the Government and the companies. The companies, whose rates are regulated by the central government, are allowed to add a 2 percent environmental surcharge to their customers' bills to finance their contribution.

The Netherlands now has more than three years of experience with this instrument. By the end of 1993, the MAP reduced CO_2 emissions by 2,100 thousand tonnes. Most of this reduction was attributable to energy conservation measures taken by the distribution companies themselves (63 percent). This positive result can be ascribed largely to the success of a subsidy program for co-generation facilities. The results were somewhat less encouraging for the two other target groups. Measures taken by households reached 32 percent of the target for the year 2000, largely because of insulation measures. The results achieved in the business and government target group were the most disappointing, with only 15 percent of their 2000 target actually achieved.

The strength of this particular instrument is that it takes advantage of the expertise present in the sector and of the existing relationship between distribution companies and their customers. This relationship provides access to millions of small-scale consumers of energy who would otherwise be much more difficult to reach with information and services. The process of drawing up and executing the MAP, moreover, contributes to internalization of environmental awareness in the energy distribution sector, which, after all, is a key link between supply and demand in the energy market.

A weakness of the MAP is that it, like the voluntary agreements, cannot furnish certainty as to whether the target will be achieved. Energy distribution companies are to a large degree at the mercy of the market in which they operate. If the price of energy remains low, demand for their energy conservation services will also remain low. They can contribute to generating this demand by means of public information campaigns, but energy prices remain a very important factor here, particularly for their commercial customers.

Carrying out the environmental action plan requires the distribution companies to see themselves in an entirely new light. Their job has always been to sell gas and electricity. Now they are being asked to do things that in effect will reduce their sales of these products. The environmental action plan asks them to redefine their self-image. Instead of seeing themselves as suppliers of gas and electricity, they have to learn to see themselves as suppliers of heat and light. This requires an enormous change in their organizational culture, which will take some time to fully realize.

Performing the activities contained in the environmental action plan also requires the outlay of financial and manpower resources on the part of the companies involved. Where their rates are regulated, the regulations will have to recognize the legitimacy of rate increases to cover the expenditures required.

5. Regulating Energy Taxes

The Netherlands introduced an environmental tax on fuels in 1988 with the object of raising revenue. The rates of this tax, which are set on the basis of the energy and carbon content of the fuels subject to the tax, are not quite high enough to have a measurable incentive effect. The amount of The Netherlands' existing tax amounts to something on the order of \$2.00 to \$2.50 per barrel of oil equivalent. The Dutch tax was introduced in order to raise revenue and not to induce changed behaviour on the part of energy producers or consumers. Introduction of a true regulating tax would most likely result in a somewhat different tax configuration.

In the second National Environmental Policy Plan, the Government announced that it will be undertaking preparations for the introduction of an (additional) tax on small-scale energy use in The Netherlands. While European Union-wide energy taxation continues to be greatly preferred, progress in this area is extremely slow. It is not certain when, if ever, the European Union Member States will decide to introduce the carbon/energy tax proposed by the Commission in 1992. Therefore the Dutch Government has prepared legislation to introduce unilaterally a tax on small-scale energy use in The Netherlands by

January 1, 1996. The tax will augment, not replace, the regulatory and administrative policy instruments that are described in greater detail in other sections.

The amount of The Netherlands' regulatory tax for small users amounts to something on the order of $10.00 per barrel of oil equivalent in 1998. The yield of the tax (1998: HGL 2.1 billion or approximately US$ 1.3 billion) will be recycled back to the households and small businesses by lowering direct taxes.

6. Conclusions

All four of the instruments contained in the mixed bag have their individual strengths and weaknesses. By using them in combination it is possible to compensate their individual weaknesses and enhance their individual strengths such that the total effect is more than the sum of the parts.

Not every instrument is equally applicable to each of the target groups of energy conservation policy. Applying all four of them to all the target groups would result in overkill, which would not be compatible with the No Regrets policy approach. It is therefore important to consider which instruments are most suitable for which target groups and how certain combinations can serve to mutually reinforce and complement each other.

Taxation is clearly not the preferred instrument for large, energy-intensive companies. Taxing the unavoidable energy use inherent to their processes erodes their profit margins without generating a commensurate environmental benefit. If the tax is not introduced world-wide, companies will tend to relocate their activities to areas where they are not subject to tax.

Voluntary agreements with these companies offer a flexible alternative to taxation, certainly in the context of a No Regrets approach. Utilizing agreements as a policy instrument requires, however, that the sectors involved are well organized with one spokesman mandated to represent them in order to avoid time-consuming, individual negotiations.

Voluntary agreements contain no sanctions for failure to live up to the commitments made. This means that they do not offer a very large degree of certainty that the policy objectives being pursued will actually be realized. This weakness can be compensated for if the measures agreed to are put into the environmental permits which companies need in order to operate their facilities. Moreover, the permitting authorities benefit from the information generated during the process of drawing up the agreements. These two instruments, then, complement one another nicely.

For households, small businesses, and other non-residential buildings, regulation in the form of individual permits is not a viable option. The numbers involved make the granting of permit applications and especially enforcement of individual regulations impractical. The same applies to voluntary agreements.

For these target groups taxation offers more potential. Taxation of smaller scale energy consumers also has the advantage that it increases demand for the energy conservation expertise present in the energy distribution sector. This provides that sector with greater opportunities to provide energy conservation services and thereby contribute to lessening the impact of the tax on energy consumers. These two instruments, too, complement one another nicely.

Although regulation in the form of individual permits is not a viable option for small businesses and other non-residential buildings, other forms of regulation may well be practical. For example, general administrative orders may be promulgated that contain requirements for categories of establishments. There can also be complementary interactions between general administrative orders and energy taxes targeted on smaller scale energy consumers. For example, if requirements relating to technology or process are based on a financial criterion (for instance, payback period), the existence of a tax will bring more options within reach.

In conclusion, then, the mixed bag certainly has merits. No one policy instrument offers a panacea. Taken together, and adjusted to the different target groups being addressed, application of the instruments contained in the mixed bag makes it possible to achieve quite a bit within the constraints of a No Regrets approach.

CENTRAL AND EASTERN EUROPEAN WORKSHOP

List of Participants

Ada Ámon
Energy Club,
Frankel Leó u. 102-104,
H-1023, Budapest, Hungary
Tel/Fax: (36-1) 212-4253/135-0975
E-mail: ADA@GEG.ZPOK.HU

Jiři Balajka
PROFING Comp. LTD, Bajkalska 27
82721, Bratislava, Slovak Republic
Tel/Fax: (427) 529-3944/522-5893

Andrea Balla
State Authority for Energy and Energy Safety,
Energy Efficiency Office,
Köztársaság tér 7, H-1081, Budapest, Hungary
Tel/Fax: (36-1) 117-4222-260/114-0276

Suzanne Billharz
Agentura pro ciste prostredi,
Jana Masaryka 1, 12000, Praha 2, Czech Republic
Tel/Fax: (422) 691-0841

Stanislav Bogdanov
National Institute of Meteorology & Hydrology,
66 Tsarigradsko chaussee 1784, Sofia, Bulgaria
Tel/Fax: (359) 272-2271 ext 224/288-0380
E-mail: STAS@OZON.RTHSF.METEO.BG

Anatoly Bordiugov
Russian Joint-Stock Company,
"Gazprom", Stroiteley Str. 8
117939 Moscow, Russia
Tel/Fax: (7-095) 133-7169/133-9700, 133-6320

Charles Buttigieg
ENE MALTA CORPORATION,
Church Whart, Marsa Malta
Tel/Fax: (00-356) 220957/243055

Vilmos Civin
Department for Environment,
Hungarian Power Co. (MVM Rt),
Vám str. 5-7, H-1118, Budapest, Hungary
Tel/Fax: (36-1) 202-1791/201-9443

Jan Corfee-Morlot
OECD Environment Directorate,
2 rue Andre Pascal,
75775 Paris CEDEX 16, France
Tel/Fax: (33-14) 524-7924/524-7876
E-mail: JAN.CORFEE-MORLOT@OECD.ORG

Lidija Cvitan
Meteorological & Hydrological Service of
Croatia, Gric 3, 41000 Zagreb, Croatia
Tel/Fax: (3854) 142-1222/127-8703
E-mail: CVITAN@CIRUS.DHZ.HR

Dmitry Danchuk
Kazakh Scientific Hydrometeorological Institute
(KAZNIGMI), Abai prospect, 32,
480072, Almaty, Kazakhstan
Tel/Fax: (7327) 254-2285/254-2539

Robert Dixon
U.S. Country Studies Program,
600 Maryland Ave. SW, Room 200 East
Washington DC, 20585, USA
Tel/Fax: (001-202) 426-0011/426-1540
E-mail: CSMT@IGC.APC.ORG

Craig Ebert
ICF, Inc., 1850 K Street, NW, Suite 1000,
Washington, DC, 20006, USA
Tel/Fax: (001-202) 862-1130/862-1144
E-mail: EBERTC@MAIL.ICFKAISER.COM

Tibor Faragó
Hungarian Ministry for Environment & Regional
Policy, Global Environment Office,
Fő utca 44-50, H-1011, Budapest, Hungary
Tel/Fax: (36-1) 201-4091

Jack Fitzgerald
US Country Studies Program,
600 Maryland Ave. SE, Room 200 East,
Washington DC, 20585, USA
Tel/Fax: (001-202) 427-0194/426-1540
E-mail: JFITZGERALD@IGC.APC.ORG

Shepa Fridman
Institute of Global Climate & Ecology,
20-b Glebovskaya St.,
107258, Moscow, Russia
Tel/Fax: (7-095) 169-2410/160-0831
E-mail: FRIDMAN@AT.IGCE.MSK.RU

Henryk Gaj
Polish Foundation for Energy Efficiency,
ul. Górskiego 7, 00-033, Warszawa, Poland
Tel/Fax: (482) 227-3271
E-mail: FUNDWAI@PLEARN.EDU.PL

Ervin Gossen
Kazakh Scientific Hydrometeorological Institute (KAZNIGMI),
Abai prospect, 32, 480072, Almaty, Kazakhstan
Tel/Fax: (7327) 254-2285/254-2539

Ferenc Halász
Hungarian Energy Office,
H-1081 Budapest, Köztársaság tér 7, Hungary
Tel/Fax: (36-1) 117-4222/210-0355

Judith Halász
Clean Air Action Group,
Ozone Working Group,
Tomori utca 23, H-1138, Budapest, Hungary
Tel/Fax: (36-1) 140-6097/140-6097
E-mail: JHALASZ@OZON.ZPOK.HU

Wim Iestra
Ministry of Housing, Spatial Planning & the Environment, Division of Climate Change, IPC 640, PO Box 30945, 2500 GX, Den Haag, Netherlands
Tel/Fax: (31) 7033-94086/7033-91310
E-mail:
IESTRA@DLE.DGM.MINVROM.NL

Bronius Jaskelevicius
Academy of Sciences,
Gedimino pr. 3, 2600, Vilnius, Lithuania
Tel/Fax: (370) 261-7709/261-8464

Karl Ernst Joerss
Umweltbundesamt, Bismarckplatz 1,
D-14193, Berlin, Germany
Tel/Fax: (4930) 8903-2373/8903-2285

Agu Karindi
Institute of Ecology, Estonian Academy of Sciences, Kevade 2, EE 0001, Tallinn, Estonia
Tel/Fax: (372) 245-0732/245-3748
E-mail: AGU@ECO.ESTNET.EE

Alexey Kokorin
Institute of Global Climate & Ecology,
20-b Glebovskaya St., 107258, Moscow, Russia
Tel/Fax: (7-095) 169-0310/160-0831
E-mail:KOKORIN@FE.IGCE.MSK.RU

Boris Kostjukovski
Institute of Energy Saving Problems,
11 Pokrovskaya St., 254070, Kiev, Ukraine
Tel/Fax: (3804) 4560-8967/4416-2358

Vladimir Kotov
Verification, Environment, Technology & Information Center,
Piluigina str., 14-1-182, 117393, Moscow, Russia
Tel/Fax: (7-095) 132-2642/132/2642
E-mail: ENIKITINA@GLAS.APC.ORG

Carolien Kroeze
Wageningen Institute of Environment and Climate Research, Wageningen Agricultural University,
P.O. Box 9101, 6700 HB, Wageningen
Netherlands
Tel/Fax: (31) 8370-85070/84839
E-mail:CAROLIEN.KROEZE@WIM-EK.CMKW.WAU.NL

Vytautas Krusinskas
Environmental Protection Ministry,
Juozapaviciaus 9, 2600, Vilnius, Lithuania
Tel/Fax: (370) 235-2138/8020

Ella Lammers
Institute for Environmental Studies,
Free University of Amsterdam,
De Boelelaan 1115, 1081 HV, Amsterdam
Netherlands
Tel/Fax: (31) 2044-49555/2044-49553
E-mail: LAMMERS@SARA.NL

Bo Lim
OECD Environment Directorate,
2 rue Andre Pascal,
75775, Paris CEDEX 16, France
Tel/Fax: (33-1) 4524-7994/4524-7876
E-mail: BO.LIM@OECD.ORG

Zoltán Lontay
EGI-Contracting/Engineering Co. Ltd.,
Bem rkp. 33-34., H-1027 Budapest, Hungary
Tel/Fax: (36-1) 201-8652/201-9216
Telex: 224461 hegi h

Nikolajs Lucans
Latvian Environment Data Centre,
Straumes St. 2, LV 2015 Jurmala, Latvia
Tel/Fax: (371) 276-4216/276-4439
E-mail: NIKOLAJS@VIDE.ORG.LV

András Lukács
Clean Air Action Group,
P.O. Box 102, H-2041 Budaőrs, Hungary,
Tel: (36-1) 206-5598, 206-5599,
Fax: (36-1) 206-5576, 140-6097
E-mail:LEVEGO@LEVEGO.ZPOK.HU

Katarina Mareckova
Slovak Hydrometeorological Institute, Department of the Environment,
Jeséniova 17, 83315, Bratislava,
Slovak Republic
Tel: (427) 373-988, 925/375-670
E-mail: KATARINA@SHMUVAX.SHMU.SK

Gregg Marland
Oak Ridge National Laboratory,
Environmental Sciences Division,
P.O. Box 2008, Oak Ridge,
Tennessee 37831-6335, USA
Tel/Fax: (001-615) 574-0390/574-2232
E-mail: GUM@ORNL.GOV

Gaida Matisone
Latvian Hydrometeorological Agency,
165, Maskavas Str., LV-1019 Riga Latvia
Tel/Fax: (371) 714-4390/714-5154

Sándor Molnár
SYSTEMEXPERT Consulting Ltd.,
Mikoviny S. u. 2-4, H-1037 Budapest, Hungary
Tel/Fax: (36-1) 250-5078/250-1713
E-mail: SMOL@URSUS.BKE.HU

Ion Moroianu
Research Institute for Environmental Engineering,
Spl. Independentei 294, sector 6, 77703,
Bucuresti 78, Romania
Tel/Fax: (401) 737-3020, 272/312-1393

Alexandr Nakhutin
Institute of Global Climate & Ecology,
20-b Glebovskaya St.
107258 Moscow Russia
Tel/Fax: (7-095) 169-2410, 160-0831
E-mail: NAKHUTIN@AT.IGCE.MSK.RU

Igor Nazarov
Institute of Global Climate & Ecology,
20-b Glebovskaya St., 107258 Moscow, Russia
Tel/Fax: (7-095) 169-2410/160-0831
E-mail:NAZAROV@DI.IGCE.MSK.RU

Csaba Nemes
Ministry for Environment & Regional Policy,
Fő u. 44-50, H-1011 Budapest, Hungary
Tel/Fax: (36-1) 201-4091/201-4091

Tamás Pálvölgyi
Ministry for Environment & Regional Policy,
Fő u. 44-50, H-1011 Budapest, Hungary
Tel/Fax: (36-1) 201-4091/201-4091

Olga Pilifosova
Kazakh Scientific Hydrometeorological Institute
(KAZNIGMI), Abai prospect 32,
480072, Almaty, Kazakhstan
Tel/Fax: (7327) 254-2285/254-2539

Jan Pretel
Czech Hydrometeorological Institute,
Na Šabatce 17, CZ-14306 Praha 4 Czech Republic
Tel/Fax: (422) 4095-111/4019-801
E-mail: PRETEL@CHMI.CZ

Klaus Radunsky
Umweltbundesamt, Spittelauer Lände 5,
A-1090 Vienna, Austria
Tel/Fax: (43-1) 31304 ext 863/31304 ext 400

Frank Rijsberman
Resource Analysis, Zuiderstraat 110,
2611 SJ Delft, Netherlands
Tel/Fax: (311) 512-2622/512-4892
E-mail: Frank.Rijsberman@resource.nl

Alexei Sankovski
ICF, Inc., 1850 K Street, NW, Suite 1000,
Washington DC, 20006, USA
Tel/Fax: (001-202) 862-1137/862-1144
E-mail:SANKOVSKIA@MAIL.
ICFKAISER.COM

Mikhail Shpirt
Institute of Fossil Fuel, Leninski prosp., 29,
117910 Moscow, Russia
Tel/Fax: (7-095) 955-4596/160-0831

Anatoly Shvidenko
International Institute for
Applied Systems Analysis, Schloss Laxenburg,
Schlossplatz 1, A-2361 Laxenburg, Austria
Tel/Fax: (4322) 3680-7497/367-1313

Tim Simmons
International Energy Agency, 2 rue Andre Pascal,
75775 Paris CEDEX 16 France
Tel/Fax: (33-1) 4524-9416/4524-1744
E-mail: TIM.SIMMONS@IEA.FR

Alissa Strauss
ICF, Inc., 1850 K Street, NW, Suite 1000
Washington DC, 20006, USA
Tel/Fax: (001-202) 862-1163/862-1144
E-mail: STRAUSSA@MAIL.ICFKAISER.COM

Katarzyna Steczko
Oil and Gas Institute, ul Lubicz 25A,
31-503 Krakow, Poland
Tel/Fax: (481) 255-8242, 255-3511
Fax: (481) 255-2963, 221-0050

Tihamér Tajthy
Technical University of Budapest
Disz tér 8, H-1014 Budapest, Hungary
Tel/Fax: (36-1) 1561-797

Tibor Takács
SYSTEMEXPERT Consulting Ltd.
Mikoviny S. u. 2-4, H-1037 Budapest, Hungary
Tel/Fax: (36-1) 1687-260 ext 178
Fax: (36-1) 1889-713

Milos Tichy
SEVEN, Slezska 7,
CZ-12056 Praha 2, Czech Republic
Tel/Fax: (422) 2424-7552/2424-7597
E-mail: SEVEN@EARN.CVUT.CZ

Zoltán Varga
RÁBA, Pf. 50, H-9002 Győr, Hungary
Tel/Fax: (36) 9-641-2111/641-3735

Gábor Vattai
Technical University of Budapest,
Műegyetem rkp. 3, Budapest, Hungary
Tel/Fax: (36-1) 463-3566/463-3560

Rolien Wams
Resource Analysis, Zuiderstraat 110,
2611 SJ, Delft, Netherlands
Tel/Fax: (311) 512-2622/512-4892
E-mail: Rolien.Wams@resource.nl

Joe Wisniewski
Wisniewski & Associates, Inc.
6862 McLean Province Circle,
Falls Church, VA, 22043, USA
Tel/Fax: (001-703) 534-3005/534-0462

GREENHOUSE GAS EMISSIONS AND RESPONSE POLICIES IN CENTRAL AND EASTERN EUROPE

Edited by:

Gregg Marland
Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge Tennessee 37831-6335, USA

Sándor Molnár
SYSTEMEXPERT Consulting Ltd., Mikoviny S. u. 2-4, H-1037 Budapest, Hungary

Alexei Sankovski
ICF, Inc. 1850 K Street, NW, Suite 1000, Washington, DC, 20006, USA

Joe Wisniewski
Wisniewski & Associates, Inc., 6862 McLean Province Circle, Falls Church, VA, 22043, USA

Sponsored by:

U.S. Country Study Program
Ministry of Housing, Spatial Planning and the Environment of the Netherlands
Hungarian Ministry for Environmental and Regional Policy

Understanding the role of greenhouse gas emissions in the global atmospheric system has become a crucial item as policy makers consider options to mitigate anticipated adverse effects to climate change. Sound data and scientific information are critical in understanding how climate may respond to human actions.

During 8-11 May 1995, the Central and Eastern European Workshop on Greenhouse Gas Emission Inventories and Response policies was held in Budapest, Hungary. Over 60 scientists from virtually all Central and Eastern Europe including the newly independent countries of the former Soviet Union gathered together. The workshop was also attended by emission inventory experts from the USA, The Netherlands, France and Germany. Over 30 presentations were made and 28 reviewed papers are published in this Special Edition publication of Journal of Időjárás. The papers present results of inventory work and discuss issues related to greenhouse gas emission estimation methodologies and response policies.

Front Cover Credits:

John Paul McCarty, ICF
Alexei Sankovski, ICF
Joe Wisniewski, Wisniewski & Associates, Inc.

Photograph of Earth from Apollo 11
Courtesy of U.S. National Aeronautics and Space Administration

IDŐJÁRÁS

VOLUME 99 * 1995

BUDAPEST, HUNGARY

AUTHOR INDEX

TABLE OF CONTENTS
I. Papers

II. Book review

III. News

IV. Contents of journal Atmospheric Environment, 1994

Contents of journal Atmospheric Environment, 1995

V. Subject index

The asterisk denotes book review

NOTES TO CONTRIBUTORS

The purpose of *Időjárás* is to publish papers in the field of theoretical and applied meteorology. These may be reports on new results of scientific investigations, critical review articles summarizing current problems in certain subject, or shorter contributions dealing with a specific question. Authors may be of any nationality but papers are published only in English.

Papers will be subjected to constructive criticism by unidentified referees.

* * *

The manuscript should meet the following formal requirements:

Title should contain the title of the paper, the names(s) of the author(s) with indication of the name and address of employment.

The title should be followed by an *abstract* containing the aim, method and conclusions of the scientific investigation. After the abstract, the *key-words* of the content of the paper must be given.

Three copies of the manuscript, typed with double space, should be sent to the Editor-in-Chief: *P.O. Box 39, H-1675 Budapest,* Hungary.

References: The text citation should contain the name(s) of the author(s) in Italic letter or underlined and the year of publication. In case of one author: *Miller* (1989), or if the name of the author cannot be fitted into the text: *(Miller,* 1989); in the case of two authors: *Gamov* and *Cleveland* (1973); if there are more than two authors: *Smith et al.* (1990). When referring to several papers published in the same year by the same author, the year of publication should be followed by letters a,b etc. At the end of the paper the list of references should be arranged alphabetically. For an article: the name(s) of author(s) in Italics or underlined, year, title of article, name of journal, volume number (the latter two in Italics or underlined) and pages. E.g. *Nathan, K. K.,* 1986: A note on the relationship between photosynthetically active radiation and cloud amount. *Időjárás 90,* 10-13. For a book: the name(s) of author(s), year, title of the book (all in Italics or underlined with except of the year), publisher and place of publication. E.g. *Junge, C. E.,* 1963: *Air Chemistry and Radioactivity.* Academic Press, New York and London.

Figures should be prepared entirely in black India ink upon transparent paper or copied by a good quality copier. A series of figures should be attached to each copy of the manuscript. The legends of figures should be given on a separate sheet. Photographs of good quality may be provided in black and white.

Tables should be marked by Arabic numbers and provided on separate sheets together with relevant captions. In one table the column number is maximum 13 if possible. One column should not contain more than five characters.

Mathematical formulas and *symbols:* non-Latin letters and hand-written marks should be explained by making marginal notes in pencil.

The final text should be submitted both in manuscript form and on *diskette.* Use standard 3.5" or 5.25" DOS formatted diskettes for this purpose. The following word processors are supported: WordPerfect 5.1, WordPerfect for Windows 5.1, Microsoft Word 5.5, Microsoft Word 6.0. In all other cases the preferred text format is ASCII.

* * *

Authors receive 30 *reprints* free of charge. Additional reprints may be ordered at the authors' expense when sending back the proofs to the Editorial Office.

Published by the Hungarian Meteorological Service

Budapest, Hungary

INDEX: 26 361

HU ISSN 0324-6329