Study of the sensitivity of the radiation regime of the atmosphere of an industrial region to variations of cloudiness and aerosol loading

V.V. Penenko and L.I. Kurbatskaya

Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk

Received March 3, 1999

A method of estimating the sensitivity of the temperature and radiation regimes of the atmosphere above industrial regions to the variation of concentrations of aerosol and gas pollutants is presented. New elements are added to the radiation block of the combined model of hydrothermodynamics of the atmosphere and pollutant transport to encode the main relations of the theory of sensitivity, namely functionals giving generalized estimates of the state of the atmosphere, and the corresponding system of adjoint equations. As a result of these modifications, we obtain algorithms allowing one to directly estimate the influence of variations of the gaseous component of the atmosphere on the state of the system as a whole, described by the generalized quality functionals.

1. Introduction

For practical purposes the need frequently arises for quantitative estimates of trends in the variation of the radiation regime of the atmosphere linked with small changes in the concentrations and distribution of optically active pollutants (greenhouse gases and aerosols), which can be due to the combined effect of natural and anthropogenic factors. Such estimates can be obtained using methods from the theory of the sensitivity of models to variations of their input parameters.[1] In the given case, the generalized parameters are the direct solar radiation flux, cloudiness, and concentrations of gaseous components and aerosols.

This paper addresses the sensitivity of mesoclimates of industrial regions, where the effect of pollutants on the quality of the atmosphere is substantial, and their impact on the radiation regime is also considerable. It is of interest in this context to answer the question, is it possible in such a situation to have instead of an “island of heat,” which is typical for the circulation of the atmosphere above cities, when the air temperature above the city is higher than above the surrounding areas, the appearance of effects of an opposite nature, i.e., an “island of cold.” The answer to this question is complicated by the fact that here it is necessary to obtain estimates on the level of small perturbations, where it is difficult to isolate the relative contribution of each factor.

There are several ways of investigating the sensitivity. One is the method of direct simulation, where the unknown variation is the difference between the solution with perturbed parameters and the solution with unperturbed parameters. However, for small variations the probability of significant errors in determining the variations arising due to differences of large quantities is high. The second way is to determine small variations of functionals of the solution, where relations are constructed between variations of the input parameters and variations of the functionals via sensitivity functions.

2. Direct estimates of the sensitivity of the radiation regime to variation of the water content

As in Ref. 2, we use a mesoregional model of the hydrothermodynamics of the atmosphere in the quasistatic approximation over a bounded territory. The radiation block in this model is updated to include a description of the cloudiness,[3] which prefigures calculation of the cloudiness field (the cloud amount is determined for any of the considered layers) by assigning a critical relative humidity which depends on the altitude and the current reference point of onset of cloud formation, where the cloud fraction c_n is estimated by relations based on the observational data.

The implemented formulas are typical for stratified cloudiness having a large spatial extent and high albedo (40–70%), which leads to a change not only in the radiation balance of the layer containing the cloudiness, but also in the radiation balance at the Earth's surface. Our model considers cloudiness of the lower and upper levels, and its fraction is calculated with the help of the following relations[5]:

$$c_m = \begin{cases} (r-65)^2/1225 & \text{at } r \ge 65, \\ 0 & \text{at } r < 65, \end{cases}$$

$$c_l = \begin{cases} (r-80)^2/400 & \text{at } r \ge 80, \\ 0 & \text{at } r < 80. \end{cases}$$

Here c_m and c_l are the cloud fraction of the middle and lower levels, and r is the relative humidity. In the presence of cloudiness the resulting fluxes of the long-

0235-6880/99/06 484-04 $02.00

wavelength and short-wavelength radiation are the sums of the corresponding fluxes ($F^{\uparrow}$, $F^{\downarrow}$ — the upwelling and downwelling fluxes, respectively, for a clear and cloudy sky). The water content of the clouds in the considered layer is given by

$$L = \gamma c_n q ,$$

where L is the water content, γ is an empirical parameter obtained from the observational data, and q is the specific humidity. The parameter γ allows one to vary the water content of a cloud, which makes it possible to consider clouds with low water content $\gamma = 0.0002$, with water content observed under real conditions in stratified clouds of types *Sc* and *As* ($\gamma = 0.002$), and with high water content ($\gamma = 0.2$).

The clouds described by the radiation model are characterized by two main optical parameters associated with their water content: the reflectance and transmittance of short-wavelength radiation. As the water content of a cloud increases for all other parameters of the model (temperature, humidity, pressure) remaining fixed, a tendency is observed toward an increase in the reflectivity (with a corresponding decrease in the transmittance) of the cloud, which is most strongly manifested for clouds of the middle level. For $\gamma = 0.002$, 0.01, 0.02, the model gives the following values of the reflectivity: clouds of the lower level: 56%, 85%, 91%; clouds of the middle level: 31%, 71%, 82%; clouds of the upper level: 2%, 9%, 18%.

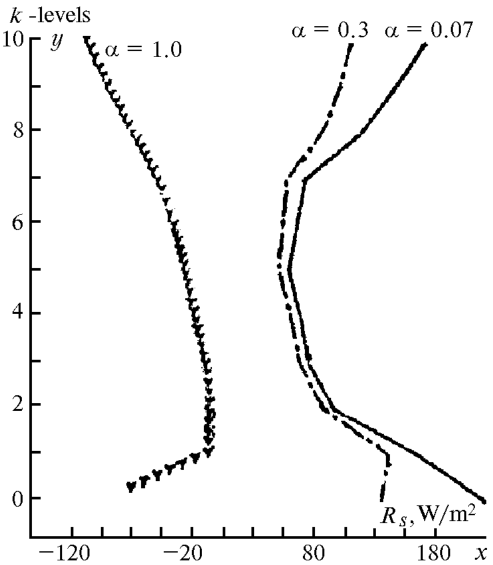

Fig. 1. Behavior of the radiation balance at the Earth's surface as a function of surface albedo and height of cloudiness. The x axis plots the value of the radiation balance R_s [W/m²], and the y axis plots the number of the calculational level at which the cloud amount is assigned ($k = 0$ at the Earth's surface, $k = 10$ at an altitude of 9 km).

Figure 1 shows profiles of the radiation balance at the Earth's surface as a function of the height of the cloudiness and the albedo of the underlying surface. At the point $k = 0$ the value of the radiation balance at the Earth's surface is written for a clear atmosphere for various values of the albedo, $k = 10$ corresponds to an altitude of 9 km. It can be seen that the value of the radiation balance at the Earth's surface R is due to two factors: the albedo of the underlying surface α and the height of the cloudiness. For $\alpha = 1$ (when the incident total solar radiation is totally reflected) R has a negative value and increases in absolute value with increase in cloudiness. For $\alpha = 0.3$, 0.07 the curves are similar to each other. This means that in the presence of clouds the albedo of the Earth's surface is less significant than in the situation of a cloudless sky, where for $\alpha = 0.07$ the value of R is 100 W/m² greater than for $\alpha = 0.3$.

Figure 2 shows a contour plot of the field of temperature differences in the steady-state regime for scenarios allowing for interaction of radiation processes with cloudiness, T_{cl}, and without it, T, at a height of 600 m above the relief of the underlying surface (surface $\sigma = 0.2$).

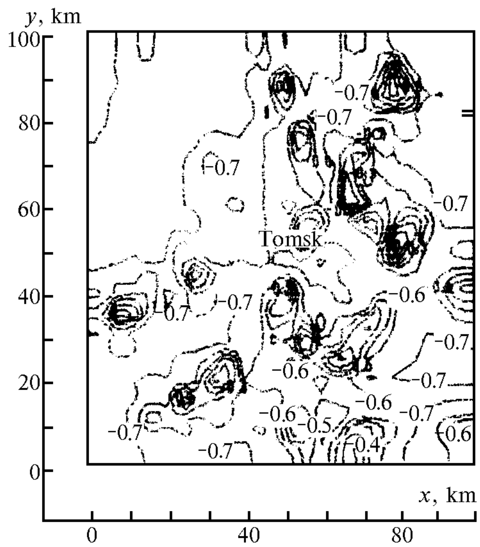

Fig. 2. Field of temperature differences in the steady-state regime for scenarios allowing for interaction of radiation processes with cloudiness T_{cl} and without it at an altitude of 600 m above the relief of the underlying surface (surface $\sigma = 0.2$).

The temperature difference for a cloudy atmosphere and for a cloudless atmosphere, averaged over the spatial variables for the prescribed level of cloudiness, is equal to −0.62°C.

3. Construction of sensitivity relations for generalized estimates of the radiation regime

To encode the main relations of the theory of sensitivity, new elements are added to the radiation block of the model: functionals giving generalized estimates of the state of the atmosphere and the corresponding system of adjoint equations.

We represent the scheme of the algorithm for calculating the sensitivity relations in the instance of a system of equations including the equations of heat transfer and transport of admixtures (aerosols, greenhouse gases, and water vapor) in the atmosphere and equations for calculating the radiative heat fluxes.[3–7]

For a compact representation of the main steps of the algorithm, we use the operator form of the equations:

$$\frac{\partial T}{\partial t} + \Lambda T - B\mathbf{R} = 0 \,, \qquad (1)$$

$$\frac{\partial \mathbf{C}}{\partial t} + \Lambda \mathbf{C} - Q_{\mathbf{C}} = 0 \,, \qquad (2)$$

$$\mathbf{R} - \tau\, \mathbf{F}_0 = 0 \,, \qquad (3)$$

$$A \times \mathbf{F}_0 - \mathbf{S}_0 = 0 \,. \qquad (4)$$

Here T is the temperature, $\mathbf{C} = \{C_i,\ i = \overline{1, n}\}$, C_i are the concentrations of the admixtures, n is the number of admixtures, Λ is a discrete analog of the advective-diffusion transport operator, $Q_{\mathbf{C}}$ are the admixture sources, B is an operator for calculating the heat flux, the flux vector $\mathbf{R} = (F^{\uparrow},\ F^{\downarrow},\ F_{\mathrm{p}})$, where $F^{\uparrow}$ is the upwelling flux, $F^{\downarrow}$ is the downwelling flux, F_{p} is the parallel flux of the direct solar radiation, $\mathbf{F}_0$ is the flux vector without taking account of absorption of radiation by greenhouse gases, $\mathbf{S}_0$ is the solar radiation flux at the upper boundary of the atmosphere, τ is a diagonal operator consisting of the transmittance functions of the greenhouse gases, A is a matrix operator whose coefficients depend on the optical properties of the atmosphere: the single-scattering albedo ω, the optical thickness of the layer Δ, and the scattering phase function, characterized by the phase factors A_1, A_2 and $A_3(\mu)$, $A_4(\mu)$, interrelated by the equations $A_1 + A_2 = 1$ and $A_3(\mu) + A_4(\mu) = 1$.

The algorithms of the theory of sensitivity were constructed using the technique described in Refs. 1 and 8. Toward this end, we define the state function and its adjoint functions as

$$\boldsymbol{\varphi} = (T,\ \mathbf{C},\ \mathbf{R},\ \mathbf{F}_0) \text{ and } \boldsymbol{\varphi}^* = (T^*,\ \mathbf{C}^*,\ \mathbf{R}^*,\ \mathbf{F}_0^*)$$

and write the variational formulation of the model (1)–(4) with the help of an integral identity. We denote the estimated functional as $\Phi^h(\varphi)$. The integral identity for this extended model is given in Ref. 4.

Taking into account the “one-dimensional” nature of the radiation block, system of equations (1)–(4) and all of the constructions for simplifying the calculations can be considered only along the vertical coordinate, assuming a parametric dependence on the horizontal coordinates. Thus, omitting all intermediate steps, we present the final results.

The system of adjoint equations:

$$-\left[\frac{\partial T^*}{\partial t}\right]^h + \Lambda^{\mathrm{T}}\, T^* + \frac{\partial \Phi^h(\varphi)}{\partial T} = 0, \quad T^*(\mathbf{x},\ \overline{t}\,) = 0 \,, \qquad (5)$$

$$-\left[\frac{\partial \mathbf{C}^*}{\partial t}\right]^h + \Lambda^{\mathrm{T}}\, \mathbf{C}^* + \left(\frac{\partial \tau}{\partial \mathbf{C}}\, \mathbf{F}^*,\ \Phi^*\right) + \left(\frac{\partial A}{\partial \mathbf{C}}\, \mathbf{F}_0,\ \mathbf{F}_0^*\right) + \frac{\partial \Phi^h(\varphi)}{\partial \mathbf{C}} = 0, \quad \mathbf{C}^*(\mathbf{x},\ \overline{t}\,) = 0, \qquad (6)$$

$$B^{\mathrm{T}}\, T^* - \mathbf{R}^* = 0, \qquad (7)$$

$$\tau^{\mathrm{T}}\, \mathbf{R}^* - A^{\mathrm{T}}\, \mathbf{F}_0^* = 0. \qquad (8)$$

Here the superscript T denotes the transpose, and the superscript h denotes the discrete analog. In Eqs. (5) and (6) derivatives of the estimated functional with respect to the grid components of the state function serve as the sources. The third and fourth terms in Eq. (6) take into account the tendencies of variation of the operators τ and A from the radiation block (3), (4) relative to the components of the vector of concentrations of the optically active admixtures. Differentiation of these quadratic forms is also realized with respect to the grid components of the vector $\mathbf{C}$. Note that Eq. (6) is a new form of the adjoint equation in the model of admixture transport. It contains additional terms allowing for the effect of changes in the quality of the atmosphere on the radiation processes. Equations (7) and (8) are the system adjoint to the radiation-block equations (3), (4). System (5)–(8) is solved in the following sequence: (5), (7), (8), (6).

Sensitivity relations

$$\delta\, \Phi(\varphi) = (\delta\, B\, \mathbf{R},\ T^*) + (\delta\, \mathbf{S}_0,\ \mathbf{F}_0^*) + (\delta\, \mathbf{Q}_C^*\,,\ \mathbf{C}^*) - [(\delta\, \mathbf{C},\ \mathbf{C}^*) + (\delta\, T,\ T^*)]_{t\,=\,0}\,, \qquad (9)$$

where the symbol δ denotes variation of the corresponding object. In formula (9) those terms have been dropped that were obtained by varying the relations of integral identity taking into account the boundary conditions. They are calculated in the usual way. Formula (9) is interesting in that all internal relations between variations of the concentrations of the optically active admixtures and radiative processes are taken into account through values of the adjoint functions. Finally, only external factors relative to the model appear in formula (9). The right-hand side of relation (9) enters as the additional term in the general sensitivity relation of the basic model allowing for the effect of variations of the heat fluxes.[9]

4. Conclusions

Radiation processes are indicators of interrelationships in a climatic system between the thermodynamics and changes in the composition of the atmosphere. It is well known that this interaction is asymmetrical in the sense that the dynamics of the atmosphere reacts to changes in air quality with a delay mediated by the radiation regime. On the basis of these two points, the relations of the theory of sensitivity are of fundamental significance. They give a picture of trends in the influence of small changes in the strength of admixture emission sources on the variation of the target functionals. These estimates are obtained on the basis of calculations with parameters of the unperturbed state of the atmosphere and the sources.

In such an approach, delayed effects are taken into account in the internal connections in the model through solutions of the corresponding adjoint problems and through the sensitivity functions. With their help, variations of the functionals are estimated directly, through variations of the input data. Such information provides a basis for identifying the preconditions for the appearance of ecologically unfavorable circumstances due to the interaction of radiation processes with atmospheric pollution, on the basis of data on emission sources.

Acknowledgments

This work was carried out with the support of the Russian Foundation of "asic Research (Grants No. 97–05–96511 and No. 98–05–65318) and the Program of Integrated Studies of the Siberian "ranch of the Russian Academy of Sciences (IG SO RAN–97 No. 30).

References

1. V.V. Penenko, *Methods of Numerical Modeling of Atmospheric Processes* (Gidrometeoizdat, Leningrad, 1981), 351 pp.
2. V.V. Penenko and L.I. Kurbatskaya, Atmos. Oceanic Opt. **10**, No. 6, 359–364 (1997).
3. V.V. Penenko and L.I. Kurbatskaya, Atmos. Oceanic Opt. **11**, No. 6, 503–506 (1998).
4. V.V. Penenko and E.A. Tsvetova, Atmos. Oceanic Opt. **11**, No. 6, 507–513 (1998).
5. J. Slingo and B. Ritter, ECMWF Tech. Rep., No. 46 (1985), 49 pp.
6. J.F. Geleyn and A. Hollingsworth, Contrib. Atmos. Phys. **52**, No. 1, 1–16 (1979).
7. *A Preliminary Cloudless Standard Atmosphere for Radiation Computations*, World Meteorological Organization, Technical Document WMO/TD 24 (1986), WCP, p. 112.
8. V.V. Penenko and E.A. Tsvetova, Bull. NCC Numerical Modeling in the Atmosphere, No. 2, 53–74 (1995).
9. V.V. Penenko, Atmos. Oceanic Opt. **12**, No. 5, 442–446 (1999).