STUDY OF HEAT ISLAND DYNAMICS WITH THE ALLOWANCE FOR AEROSOL CONTRIBUTION INTO THE RADIATION PROCESSES

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Received February 4, 1998

We describe the radiation block adapted to the mesoregional model of the atmosphere that is used to study the conditions under which mesoclimate of an industrial region is formed. The results of numerical experiments presented in the paper show that inhomogeneities in the distribution of aerosols and trace gases in the atmosphere may influence the structure of meteorological fields. The influence is due to thus caused variations in the radiation heat influx.

1. INTRODUCTION

The aim of this paper is to incorporate the radiation block into the mesoregional model of the atmospheric hydrothermodynamics, in a quasi-static approximation on a limited territory, for estimating the characteristic scales of the influence the inhomogeneities in the radiation heat fluxes may have on the mesoclimate dynamics.[1] We study the processes that are characteristic of the atmosphere over industrial regions in Southern Siberia.

The main sources of the underlying surface inhomogeneities, which may affect the formation of mesoclimate, are urban heat islands and contrasts of temperature of the water-land type with seasonal and diurnal changes of sign. The changes manifest themselves as islands of heat or cold.

The radiation block describes the processes in the atmosphere that occur with the participation of long-wave and short-wave radiation including interactions with the minor gaseous constituents (water vapor, carbon dioxide, methane, ozone) and aerosols of natural and anthropogenic origin in a particular climate system.[2,3]

In real atmosphere, the concentration fields of atmospheric pollutants vary in time and space. The fields of their optical properties, chemical composition, and microstructure may undergo variations as well. The latter circumstance makes it difficult to obtain such estimates. Therefore, to arrange scenarios for the simulation, we have specially formed certain optimal conservative situations. In so doing, we have constructed standard aerosol models each being most typical for one or another area of the region considered. The composition of aerosol is limited by three main components: soot, dust, and water-soluble particles. Populated areas and towns with higher soot content are considered to be the most polluted. Dust is supposed to be the dominating component over fields, marshland, and water surface in spring and summer-fall seasons.

2. THE STRUCTURE OF THE RADIATION BLOCK

The model we use for calculating the radiation heat fluxes is based on the system of differential equations of radiation transfer in a two-flux Addington approximation for a horizontally homogeneous atmosphere.[2] The short-wave region of the radiation spectrum contains the parallel flux of direct solar radiation (S) and fluxes of down going ($F^{\downarrow}$) and up going ($F^{\uparrow}$) scattered radiation; the long-wave region contains fluxes of up going ($F^{\uparrow}$) and down going ($F^{\downarrow}$) radiation. To construct parametrization formulas, the atmosphere is divided into n layers along the vertical direction, with the optical properties of the atmosphere assumed to be constant within each layer. Under these assumptions, the system of differential transfer equations is analytically integrable within a layer. As a result, we obtain a system of discrete equations relating the values of the sought fluxes at the boundaries of cells

$$\begin{pmatrix} a_1 & 0 & 0 \\ a_2 & a_4 & a_5 \\ a_3 & a_5 & a_4 \end{pmatrix}_j \begin{pmatrix} F_{\mathrm{p}}^{\mathrm{t}} \\ F_{\mathrm{d}}^{\mathrm{t}} \\ F_{\mathrm{u}}^{\mathrm{b}} \end{pmatrix}_j = \begin{pmatrix} F_{\mathrm{p}}^{\mathrm{b}} \\ F_{\mathrm{p}}^{\mathrm{b}} \\ F_{\mathrm{u}}^{\mathrm{a}} \end{pmatrix}_j \quad j = \overline{1, n}\,. \tag{1}$$

Here $F_{\mathrm{p}} \equiv S$ is the down going parallel flux of solar radiation; $F_{\mathrm{d}} \equiv F^{\downarrow}$ is the down going flux of scattered short-wave radiation; $F_{\mathrm{u}} \equiv F^{\uparrow}$ is the up going flux of scattered radiation (indices b and t mean the values on the lower and upper boundaries of layers, respectively); a_{1j}, a_{2j}, a_{3j} are the coefficients of transmission, diffuse transmission, and diffuse reflection of parallel solar fluxes; a_{4j}, a_{5j} are the coefficients of transmission and reflection of scattered radiation, respectively, for a layer with the number j.

The coefficients $a_{ij} \equiv a_{ij}(\delta\tau,\ \omega,\ \tilde{\beta},\ \mu_0,\ \beta(\mu_0))$ are calculated analytically; $\delta\tau$ is the optical thickness of

0235-6880/98/06 503-04 $02.00

the layer; ω is the single scattering albedo; μ_0 is the zenith angle of the Sun; $\beta(\mu_0)$ is the forward scattering phase function for parallel solar rays; $\tilde{\beta}$ is the backscattering phase function for diffuse rays.

The system (1) consists of $3n$ equations with $3(n+1)$ flux values sought. To close the system, the following boundary conditions are set:

$$F_{\mathrm{p}}(0) = \mu_0 S_0,$$

$$F_{\mathrm{d}}(0) = 0 \tag{2}$$

for short-wave radiation at the upper boundary of the atmosphere and

$$F_{\mathrm{u}}(g) = A_{\mathrm{g}}(\mu_0)\, F_{\mathrm{p}} + A_{\mathrm{g}}\, F_{\mathrm{d}}. \tag{3}$$

at its lower boundary. Here S_0 is the solar constant at the upper boundary of the atmosphere; $A_{\mathrm{g}}(\mu_0)$, A_{g} are albedos of the Earth's surface for short-wave direct and scattered radiation, respectively.

The system of linear equations (1)–(3) is solved by use of Gaussian elimination for band matrices. Similar system of equations but with 2×2 partitioned matrices is obtained for long-wave fluxes as well. It contains $2(n+1)$ unknown variables. The boundary conditions for long-wave fluxes are as follows:

$$F_{\mathrm{d}} = \pi B,$$

at the upper boundary of the atmosphere and

$$F_{\mathrm{u}} = (1 - E_{\mathrm{g}})F_{\mathrm{d}},$$

at its lower boundary. Here E_{g} is the Earth's emissivity.

In this paper, in contrast to Refs. 2 and 3, consideration of Rayleigh scattering, scattering and absorption by aerosol (whose particles are comparable in size with air molecules) and clouds (if they are present) involves the aerosol[4–6] of rather large optical mass. This aerosol consists of several components such as soot, dust, water-soluble substances. Besides, we estimate the influence of such aerosols on radiation and, consequently, on radiation heat influxes (short-wave and long-wave ones). Thus, the total optical thickness $\tau_{\Delta z}$,[6,7] spectral albedo ω, and coefficients of scattering phase matrices β and $\beta(\mu_0)$ are calculated in a layer depending on the coefficient value β_ν which is equal to the sum of scattering, σ_ν, and absorption, k_ν, coefficients of separate components in the layer

$$\delta\tau \equiv \tau_{\Delta z} = \sum_{\alpha=1}^{m} \int_{z}^{z+1} \beta_{\nu,\alpha}\, \mathrm{d}z, \tag{4}$$

where the subscript α refers to the optical mass of a separate pollutant; m is the number of substances attenuating the radiation.

The transmission function ψ of a layer characterizes attenuation of short-wave and long-wave radiation fluxes by a given aerosol. It is defined by the relation $\psi = \exp(-\tau_{\Delta z})$.

The calculation scheme for radiation fluxes involves two steps. At the first step, the scheme takes into account the processes of Rayleigh scattering and those of radiation absorption and scattering by clouds (if they are present) and, in addition, aerosols that are introduced into the radiation model. After the first step is completed, we obtain the values of fluxes (short-wave and long-wave ones) undergoing variations due to the above enumerated radiation processes. At the second step, the scheme takes into account absorption of radiation by gases (H_2O, CO_2, and O_3). For this purpose, we introduce a special procedure to calculate the transmission function in different frequency intervals into which the spectrum of radiation considered is divided. In the case we analyze here, the short-wave spectrum is divided into two intervals, and the long-wave one into the three ones.

The radiation model is realized as a vertically one-dimensional in the region $0 \le p \le P_{\mathrm{s}}$, $P_{\mathrm{s}} = P_{\mathrm{s}}(x, y, t)$ is the pressure near the surface; x, y, t are the horizontal coordinates and time at every node of the horizontal grid of the hydrodynamic model of the atmosphere. The above-stated horizontal homogeneity of optical properties of the atmosphere is assumed to be valid within a single horizontal cell. That means that optical properties of the atmosphere are set by step functions being parametrically dependent on the coordinates x, y, and t.

3. RESULTS OF NUMERICAL EXPERIMENTS

The numerical experiments we have carried out deal with the analysis of atmospheric situations characterized by different composition of optically active components. The relative content (in percents) and corresponding optical properties were the input parameters to the model. The simulation scenarios differ by optical thickness of the atmosphere that was supposed to be linearly related to the scattering and absorption coefficients.

Vertical distributions of the main gaseous components of the atmosphere were set in the interval $[0 \le p \le P_{\mathrm{s}}]$ at each point of the horizontal grid. In the lower layers, up to a height of 3 km over the terrain, those were supplemented with distributions of aerosol and trace gas components. Since the study was conducted for the atmosphere over an industrial region, the model aerosol composition at every point of the horizontal grid was formed in accordance with the type of the underlying surface and land use categories. Calculations were performed for the same area and with the same input information as in Ref. 1.

Territories of the town and settlements are considered as most polluted parts of the area. So, vertical distributions of industrial aerosol with high content of soot were formed at the corresponding grid points. Territories occupied by forests and marshes are believed to be most clean. Distributions of continental aerosol with high content of dust in the layer from the Earth's surface and up to 1.5 km height over the terrain were formed at the grid points corresponding to fields.

To exclude influence of cloud cover which is significant against the background of all other radiation processes taken into account in the radiation model, the vertical distribution of water vapor is set so that the relative humidity does not exceed 50% in the vertical column of the atmosphere. This restriction makes it possible to estimate pure aerosol influence because no cloud cover is formed under relative humidity below the accepted one.[8]

The Table I presents calculated fluxes of direct and scattered (up going and down going) solar radiation at the upper boundary and at the Earth's surface for two aerosol models: industrial and continental (described in Refs. 5 and 6), and for the aerosol-free model of the atmosphere.

All the initial situations for the simulation scenario differ both in content of aerosol components and their optical properties: industrial aerosol is rich in soot (21%), while the continental aerosol is characterized by higher content of dust. Besides these two types of aerosols no other conditions have been varied, i.e., distributions of temperature, humidity, and pressure along height were the same. The value of the Earth's surface albedo was taken to be 0.3, zenith angle was set to be equal to 0.9167 and, consequently, solar radiation coming to the upper boundary of the atmosphere, was equal to 1272 W/m^2.

The differences in aerosol composition and properties have an effect on the behavior of direct and scattered solar radiation. For instance, industrial aerosol has higher absorptance as compared to that of the continental one due to the presence of soot and, naturally, a layer containing such aerosols will get warm due to absorption of solar radiation (mainly direct). Continental aerosol, in its turn, scatters light, so the incoming solar radiation will rather be scattered than absorbed in a considered layer. However, the effect of heating is present but it manifests itself weaker in such a layer.

As for long-wave radiation, cooling due to continental aerosol effect is much stronger as compared that in the case with the industrial aerosol. The behavior of fluxes for other aerosol models appears to be similar, and difference between the models manifests itself in the intensity of direct and scattered radiation[8] fluxes reaching the Earth's surface.

It should be noted that the heat influxes caused by long-wave radiation much strongly respond to the continental aerosol.[7] Cooling of the layer containing the dust component increases with the increasing content of this component. However, the total effect of cooling of the considered layer due to long-wave radiation and heating due to short-wave radiation is insignificant. In this sense, the effect caused by industrial aerosol is unbalanced because this aerosol favors strong heating of the layer due to absorption of short-wave radiation by soot.

TABLE I.

Aerosol model	Fluxes at h = 3000 m	Fluxes at the level of the Earth's surface
Industrial aerosol		
$F_{\mathrm{p}}^{\downarrow}$	926.85	400.70
$F_{\mathrm{d}}^{\downarrow}$	83.39	112.96
$F_{\mathrm{u}}^{\uparrow}$	−163.61	−118.04
F_{ef}	846.64	395.62
ΔF_{ef}	–	451.02
Continental aerosol		
$F_{\mathrm{p}}^{\downarrow}$	926.25	307.93
$F_{\mathrm{d}}^{\downarrow}$	100.89	248.51
$F_{\mathrm{u}}^{\uparrow}$	−307.33	−139.20
F_{ef}	720.42	417.24
ΔF_{ef}	–	303.18
Clear atmosphere		
$F_{\mathrm{p}}^{\downarrow}$	946.85	841.49
$F_{\mathrm{d}}^{\downarrow}$	75.55	105.15
$F_{\mathrm{u}}^{\uparrow}$	−208.28	−208.27
F_{ef}	813.48	738.37
ΔF_{ef}	–	75.11

Comment. F_{ef} is the efficient radiation flux at the given level; ΔF_{ef} is the difference between the fluxes at the boundaries of the lower 3 km layer of the atmosphere.

Comparative analysis of the results of numerical experiments permits one to conclude that the industrial aerosol leads to an increase in temperature in a layer with higher aerosol content due to absorption of short-wave radiation by soot; while in the lower layers, there is a trend to a temperature decrease. The continental aerosol also leads to an increase of atmospheric temperature but it is weaker. As to the part of the region where the aerosol-free model was used, the temperature variation was only insignificant.

It is also to be noted that the presence of one or other aerosol has also an effect on the radiation balance of the Earth's surface what is seen in the Table. The Figure 1 presents the difference in temperatures taking place in the presence of aerosol and without it. One can see that the maximum temperature difference is characteristic of the part of the area considered where the grid nodes fall into an urban area. Therefore, if aerosols are taken into account in the radiation model, the heat island effect over the town increases due to the changes in short-wave heat influxes.

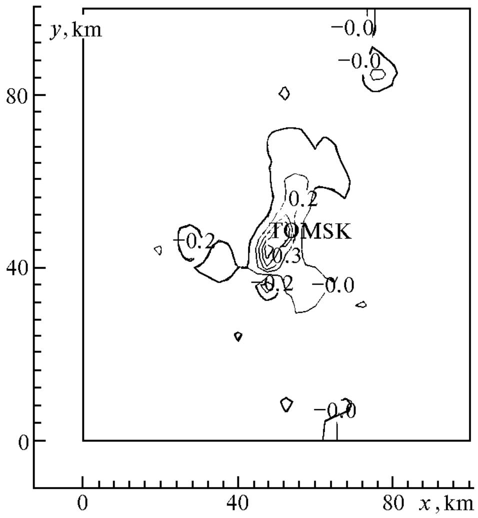

FIG. 1. The field of temperature difference in the steady regime for scenarios taking into account interaction of radiation with aerosols T_a and ignoring interaction T at a height of 300 m *over the underlying surface (surface with* $\sigma = 0.1$*).*

4. CONCLUSION

As follows from the experiments performed, the effect that aerosol may produce on the thermodynamics of the atmosphere over industrial regions can be significant. That means that mathematically modeling the atmospheric processes, for the forecast and analysis purposes, certainly needs for the account of interactions of the solar radiation with the aerosols and optically active gases of the atmosphere. In concrete situations their influence manifests itself in different ways. As a consequence one cannot unambiguously estimate importance of one or other factor among the variety of factors acting in a climate system. For these reasons the radiation block must be sufficiently versatile in its functional purpose and easy to perform.

ACKNOWLEDGMENT

This work has been supported by the Russian Foundation for Basic Researches (Project 97–05–96511) and integration grant IG SB RAN–97 No. 30.

REFERENCES

1. V.V. Penenko and L.I. Kurbatskaya, Atmos. Oceanic Opt. **10**, No. 6, 359–364 (1997).
2. J.F. Geleyn and A. Hollingworth, Beitr. Phys. Atmosph. **52**, No. 1, 1–16 (1979).
3. G.P. Kurbatkin and L.I. Kurbatskaya, "*The study of responsivity of radiation heat influxes to cloud cover,*" Preprint No. 686, Computer Center, Siberian Branch of the Russian Academy of Sciences, Novosibirsk (1986), 33 pp.
4. V.N. Krupchatnikov and L.I. Kurbatskaya, in: *Numerical Models in Problems of Atmospheric Physics and Environmental Monitoring* (Novosibirsk, 1987), pp. 48–60.
5. *A Preliminary Cloudless Standard Atmosphere for Radiations Computation,* WMO/TD-24. 1986. WCP. 112.
6. V.N. Krupchatnikov and L.I. Kurbatskaya, in: *Numerical Simulation in Problems of Atmospheric Dynamics and Environmental Monitoring* (Novosibirsk, 1989), pp. 55–66.
7. V.N. Krupchatnikov and L.I. Kurbatskaya, in: *Hydrodynamic Models of the Environment* (Novosibirsk, 1990), pp. 60–67.
8. N.C. Tody and G.B. Stanley, J. Atmos. Sci. **37**, 193–213 (1980).