Eddy-resolving models in problems of vertical transport of aerosols

V.M. Mal'bakhov and V.A. Shlychkov*

Institute of Computational Mathematics and Mathematical Geophysics,
Siberian Branch of the Russian Academy of Sciences, Novosibirsk
**Novosibirsk Affiliate of the Institute of Water and Ecological Problems,*
Siberian Branch of the Russian Academy of Sciences, Novosibirsk

Received July 24, 2002

Peculiarities of the vertical transport of heat, moisture, and aerosol under convective conditions are investigated based on analysis of two numerical models of a convective ensemble: eddy-resolving and simplified ones. The models developed by us and suitable for solving the problems of aerosol diffusion and constructing the convection parameterization procedures in global circulation models are reviewed. Some recommendations are given for using the models for solution of applied problems.

Introduction

According to observational data, under conditions of stable stratification, the aerosol particles entering from the underlying surface do not rise higher than the ground layer of several meters thick. However, at developed convection typical of the summer season, there appear conditions favorable for vertical transport of aerosol up to the heights of 1–2 km, and under convective cloudiness aerosol reaches the tropospheric top. At such heights, aerosol can be transported thousands of kilometers far from its source. Besides, under convective conditions the rate of the vertical aerosol transport increases considerably due to the capability of atmospheric convection to generate relatively large quasiordered structures – thermics and cumulus clouds up to several kilometers in size and vertical rates to several meters per second. Such structures are now referred to as coherent ones.

It should be noted that traditional models of turbulent diffusion – both static and hydrodynamic – fail to describe implicitly the evolution of the coherent structures, and therefore they fail to explain many peculiarities of aerosol diffusion under convective conditions. The Large Eddy Simulation (LES) approach is free of these shortcomings. In this approach, distortions of more than 100 m in size are resolved implicitly with the use of equations of fluid dynamics accounting for the processes of cloud and precipitation formation, and smaller distortions are parameterized as subgrid turbulence.[1–3] The aims of this paper are the following:

– to demonstrate the capabilities of the eddy-resolving[1,4] and simplified LES models[5–7,11,12] developed by us for simulation of different types of convective ensembles;

– to study some typical scenarios of aerosol exchange between the surface and the atmosphere and the vertical aerosol transport under conditions of the developed convection[4–6];

– to compare the calculated results with observations and with some existing LES.

1. Physical processes and mathematical model

It is commonly known that the most part of atmospheric aerosol originates from the surface. Its sources are sand and dust from unplanted areas, salt particles from evaporated water droplets coming to the atmosphere from the water surface, and other aerosols of natural and anthropogenic origin. Thus, the model includes a block accounting for exchange processes between the land or water surface and the atmosphere. Above the surface there is a 10–100 m thick layer of continuous flows. The turbulent mixing in this layer can be described parametrically based on the Monin–Obukhov similarity theory. In the upper-lying atmospheric boundary layer, processes of penetrative turbulent convection develop, and just these processes are responsible for quick aerosol transport to rather high (up to 10 km) altitude.

Convection is caused by heat influx from the surface due to insolation. Convective exchange is realized as an ensemble of coherent structures, being an unordered set of thermics of various sizes and intensities and cumulus or cumulonimbus clouds of various types. In the eddy-resolving models, the structural elements of the convective ensemble are interpreted as large eddies in the turbulence field and are the objects of direct numerical reconstruction.

The problem of describing the stochastic ensemble of large eddies is mathematically formulated in Refs. 1 and 6. The initial differential equations describe the ordered transfer and turbulent diffusion of air, heat, water vapor, aerosols, and water droplets. Two fractions of liquid atmospheric moisture are considered, namely, the suspended cloud fraction and the heavy rain one with its own falling rate. The equations account for the processes of vapor condensation and droplet growth due to condensation, evaporation of cloud and rain water. Droplets may also grow due to coagulation occurring at their collision.

2. Types of convective ensembles

The model from Ref. 1 describes different types of atmospheric convection depending on vertical distribution of the mean wind, temperature, and humidity. Convective conditions were studied thoroughly in Ref. 6 based on calculations by the 2D version of the model. It turned out that the both models from Refs. 1 and 6 describe, in essence, the same convection types, including single-layer and two-layer convection. The single-layer cloud convection develops in the form of thermics and small cumulus clouds and is usually observed above the tropical ocean at low amplitudes of the diurnal temperature variation and high vapor content in air. Convective activity gives rise to the mixing layer about 1 km thick, in which the relative humidity is close to its saturation value. The mixing layer is topped by a thin inversion sublayer, above which the humidity is much lower than the saturation value.

In the case of single-layer convection, clouds usually give no precipitation, and vapor and liquid water are transported into mid-latitudes. Therefore, this convection substantially contributes to the global water cycle. A great number of papers are developed to modeling of single-layer convection.$^{1-9}$ Convection characteristics obtained by different models are intercompared with each other and compared with observations in Fig. 1.

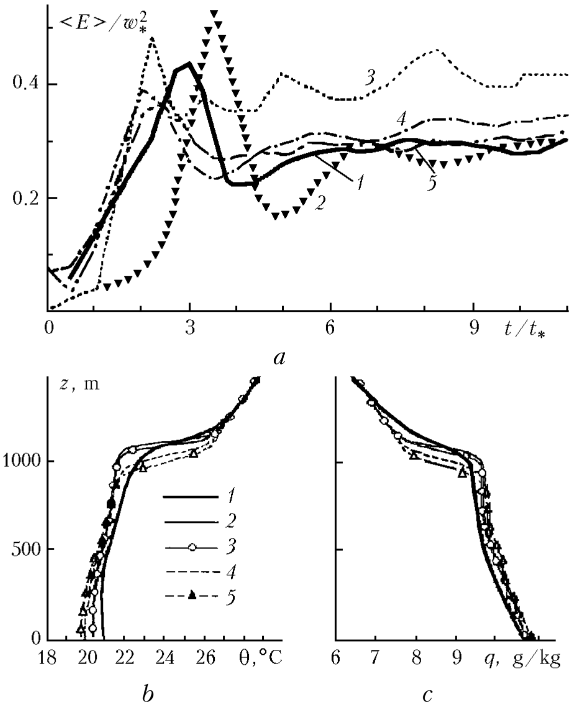

Fig. 1. Comparison of model results with observations: (*a*) time behavior of kinetic energy in the model[1] (curve *1*) and four LES according to Ref. 2 (curves *2–5*); (*b*) vertical profiles of equivalent potential temperature in the model[1] (curve *1*) and LES according to Ref. 3 (curves *2–5*); (*c*) liquid water content profiles.

Under continental mid-latitude conditions characterized by a high amplitude of diurnal variation and smaller amount of vapor in lower layers, clouds already at the initial stage come off the parent thermics and form the second convective layer (two-layer convection). Cloud cells are usually much larger than thermics. If the vertical dimension of the second-level clouds exceeds one kilometer, they can give precipitation.

Under normal conditions, thermics and convective clouds often form larger quasiordered conglomerates with a long lifetime called supercells. The model[1] describes the basic types of supercells shown in Fig. 2.

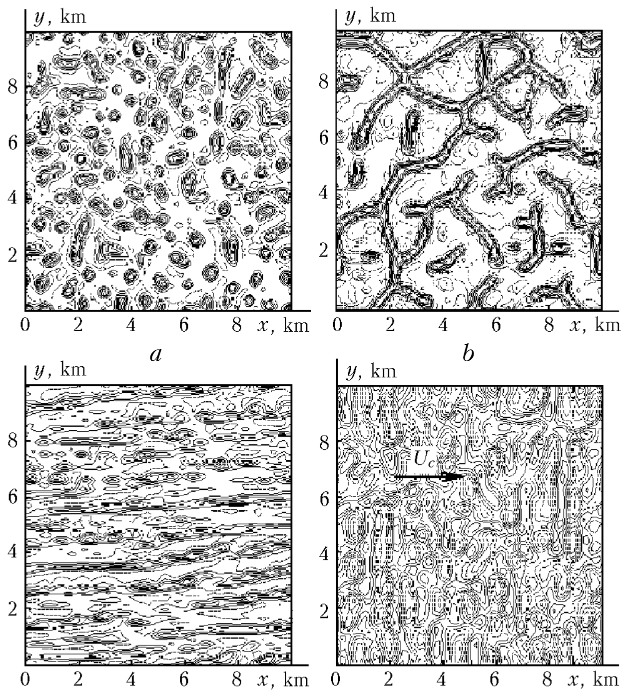

Fig. 2. Horizontal cross section of vertical velocity at the height of 500 m: chaotic arrangement of convective cells (*a*), hexagonal structures at gentle breeze (*b*), convective paths oriented along the velocity vector (*c*); cross structures at large wind shift (*d*).

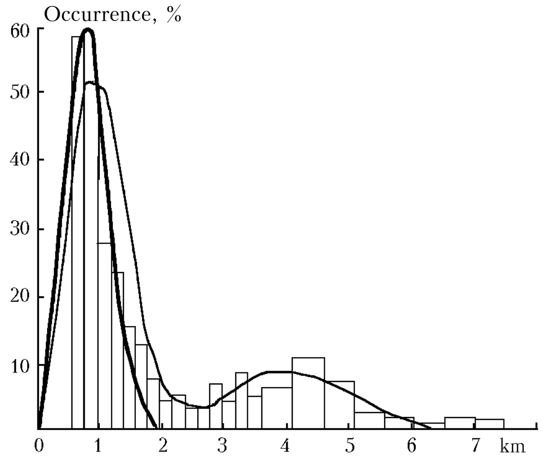

Fig. 3. Cloud size occurrence with respect to diameter *D*: measurements[10] (rectangles); calculated distribution at chaotic cloud arrangement (thick curve); calculated distribution in a system with supercells (thin curve). Left peak corresponds to small clouds; right one corresponds to convective supercells.

Calculated and actual distributions of cloud cells and supercells are compared in Fig. 3.

3. Arid aerosol exchange between the land and the atmosphere

The mass exchange between the surface and the atmosphere was studied in Ref. 4. The surface covered by fine dust or sand particles serves a source of aerosol. In Ref. 4 it was shown that the aerosol is concentrated in upward current zones of supercells, whose size and lifetime exceed those of individual thermics. This result is confirmed by measurements conducted by the Institute of Atmospheric Physics RAS in Kalmykiya semideserts.[8] In the data of field observations and in calculations, the characteristic scales of areas with the increased aerosol concentration are close, and the extreme concentration values agree quite well. The vertical profile of the horizontally averaged aerosol concentration peaks near the surface, quickly decreases in the layer of constant flows and almost does not change in the convective mixing layer. It should be noted that turbidity of the whole convective layer is a well-known fact. The concentration of aerosol particles in the convective layer is roughly inversely proportional to the free particle falling rates.[6] This is also confirmed by measurements. A small portion of aerosol comes to the second convective layer, where aerosol particles serve as condensation nuclei for formation of water droplets and crystallization nuclei for hailstones.[5,6]

4. Aerosol washout

It should be noted that convection not only is the very efficient mechanism of vertical transport of pollutants, but it can also affect the air purification processes. In Ref. 9 it was shown that rain of moderate intensity clears the atmosphere from arid aerosol for 15–20 min, which is confirmed by observations.

5. Aerosol exchange between the ocean and the atmosphere

The mechanism of aerosol income from the ocean surface into the atmosphere is very significant for the global climate. Wave collapse at strong wind results in formation of foam consisting of a great number of air bubbles, which, bursting, supply the atmosphere with water droplets. Under the conditions of stable stratification, the most part of the droplets returns into water, but convection favors the carry-out of water particles into the lower and middle troposphere. The droplet water quickly evaporates, and a huge amount of salt particles are formed in the atmosphere. Just these particles are the main source of condensation nuclei for water vapor in formation of clouds and precipitation. This mechanism of aerosol income into the atmosphere was described in Ref. 5, and the qualitative pattern of the marine aerosol distribution is similar to that of the arid aerosol.

6. Parametric consideration of atmospheric convection

Because of requirements to the space and time resolution imposed on eddy resolving models, the LES approach cannot serve a basis in calculation of large-scale currents, for example, in global circulation models (GCM) or global climate models. The convective exchange processes in this case are taken into account with the use of relatively simple models that do not demand large computer resources. The simplified model of convective ensemble proposed in Refs. 6, 7, 11, and 12 meets the last criterion. To find the domain of applicability, we have compared the results of calculation by the eddy-resolving[1] and the simplified models. It turned out that under the same conditions the both models describe the same types of convective supercells (see Fig. 2). The correctness of the theory is supported by satellite cloud images. This circumstance gives grounds to use the simplified model for parameterization of atmospheric convection in GCM. Let us list the aspects of the possible use of the simplified model:

- calculation of convective fluxes of momentum, heat, and moisture in GCM;
- numerical interpretation of large-scale prognostic fields through detailed description of the infrastructure of cloud ensembles;
- reconstruction of the vertical structure of mean fields of wind, temperature, and humidity from satellite images of cloud cover in the case of convection. The theory shows that every type of convective supercells easily identified from satellite cloud images is characterized by rather narrow range of weather parameters.

Conclusion

Under the conditions of developed convection, the eddy-resolving approach has indisputable advantages over the traditional diffusion and statistical approaches in calculation of the vertical aerosol transport. The models from Refs. 1 and 6 are presented here as a hydrodynamic base for solving problems of monitoring and prediction of aerosol pollution in the atmospheric boundary layer. Thus, consideration of the processes of chemical transformation of pollutants extends the range of problems due to description of acid rains and spreading of hazardous pollutants from urban sources, as well as allows solution of other problems of short-range transport. As applied to the Siberian region, the most urgent problems are convective transport of aerosol over industrial zones and forest fires, as well as vertical transport of greenhouse gases originating from the wetlands of Siberian taiga, tundra, and forest-tundra.

Acknowledgments

The authors are gratefully indebted to Prof. P.Yu. Pushistov for useful discussions.

References

1. V.A. Shlychkov, V.M. Mal'bakhov, and P.Yu. Pushistov, Atmos. Oceanic Opt. **14**, No. 10, 881–884 (2001).
2. M.F. Khairoutdinov and E.L. Kogan, J. Atmos. Sci. **56**, No. 13, 2115–2130 (1999).
3. F.T.M. Niestadt, P.J. Mason, C.-H. Moeng, and U. Schuman, in: *Selected Paper from the 8th Symposium on Turbulent Shear Flow* (Springer-Verlag, 1991), pp. 343–367.
4. V.A. Shlychkov, P.Yu. Pushistov, and V.M. Mal'bakhov, Atmos. Oceanic Opt. **14**, Nos. 6–7, 527–531 (2001).
5. V.M. Mal'bakhov and P.Yu. Pushistov, Atmos. Oceanic Opt. **11**, No. 8, 785–788 (1998).
6. V.M. Mal'bakhov, *Hydrodynamic Simulation of the Evolution of Atmospheric Convective Ensembles* (ICMMG SB RAS Publishing House, Novosibirsk, 1997).
7. V.M. Malbackov, J. Fluid Mech. **365**, No. 1, 1–22 (1998).
8. G.I. Gorchakov, P.O. Shishkov, V.M. Kopeikin, et al., Atmos. Oceanic Opt. **11**, No. 10, 958–962 (1998).
9. V.M. Mal'bakhov, P.Yu. Pushistov, and V.A. Shlychkov, in: *Abstracts of Reports at 8th Workgroup on Siberian Aerosols,* Tomsk (2001), pp. 61–62.
10. M.A. LeMone, T.C. Chang, and C. Lucas, J. Atmos. Sci. **51**, No. 22, 3344–3350 (1994).
11. V.M. Mal'bakhov, Meteorol. Gidrol., No. 11, 30–39 (1997).
12. V.M. Mal'bakhov and V.A. Perov, in: *Computational Processes and Systems*, ed. by G.I. Marchuk (Nauka, Moscow, 1993), Issue 10, pp. 96–136.