LIDAR NEPHELOMETRIC SOUNDING OF ARID AEROSOL

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The structure of the aerosol convective boundary layer of the atmosphere is studied. It is shown that the vertical transfer in the boundary atmospheric layer has a structure of large-scale convective cells. The process of wind carry-over of aerosol from the underlying surface under conditions of convection is revealed. This process is determined by wind gusts about 100 s *long.*

Study of the transformation processes in the ground atmospheric layer has shown that, as a rule, the ground layer cannot be considered isolated from the boundary atmospheric layer. That is why we have stated the problem to investigate into formation of aerosol in the boundary atmospheric layer. The consequent problem is to develop the system of methods and means for control over characteristics and "elementary" processes of aerosol transformation in the boundary atmospheric layer.

In 1996–1997, when conducting field measurements of characteristics of arid aerosol in the boundary atmospheric layer at the territory of Kalmykiya, it was revealed that in summer the boundary atmospheric layer is, as expected, convective in daytime.[1] This leads to the necessity of studying the modes of formation of the convective aerosol boundary layer of the atmosphere in the arid zone.

For the necessity to control atmospheric processes in the wide range of variability of spatial scales, the research groups of some Russian institutes (Institute of Atmospheric Physics, L.Ya. Karpov Research Institute of Physical Chemistry, and Institute of Experimental Meteorology) have equipped an airborne laboratory. This laboratory is based on an Antonov–2 light airplane equipped with the means for local control and remote sounding.

The authors have conducted the following measurements. The vertical distribution of aerosol along the flight path was sounded with a small-sized lidar (radiation wavelength 1.06 μm, output power in a pulse 0.2 J) directed at nadir.

The vertical resolution in lidar signal processing was restricted to intervals of 30 or 50 m depending on the level of turbidity of the atmospheric boundary layer. Characteristics of the arid aerosol were recorded with an airborne nephelometer and particle counter. In 1997, the laboratory was additionally equipped with the satellite navigation system for fast control over the airplane coordinates.

In the ground atmospheric layer, aerosol characteristics and meteorological parameters were measured at stationary sites and with the equipment of a mobile laboratory on ZIL–130N lorry. The mobile laboratory includes nephelometers, aerosol particle counters, and an automated mast complex. This complex allowed us to measure the vertical temperature lapse rates and the wind velocity with the temporal resolution ≥ 1 s.

The measurements described below were a part of the large-scale experiment on studying of dust transfer with the participation of several research groups.[2]

Since the experimental study of the convective boundary layer is very problematic, numerical modeling of convective processes in the boundary layer, including that under cloudiness conditions, is widely used now. The results of laboratory modeling of convective conditions are also used rather widely.

The literature analysis has shown that the data of our measurements are in a good agreement with the modern detailed concepts of the convective mode of the boundary atmospheric layer. Figure 1 presents some examples of the vertical aerosol distribution along the flight path in the boundary atmospheric layer on July 15, 1997 (Fig. 1*a*) and July 25, 1997 (Fig. 1*b*).

The repeatedly observed quasi-periodic ("coherent") structure is clearly seen in Fig. 1*b*. This structure consists of upright convective cells with the horizontal size of 5–6 km. Alternate dark and light bands are connected with zones of downward and upward flows. The dark bands correspond to the aerosol backscattering coefficient $\beta_\pi > 2\cdot10^{-3}$ km$^{-1}\cdot$sr^{-1}, and light bands (and areas of an arbitrary shape) correspond to $\beta_\pi < 2\cdot10^{-4}$ km$^{-1}\cdot$sr^{-1}.

Due to relatively weak turbidity of the boundary layer and the middle troposphere, as well as due to the presence of a surface aerosol source (dried, as a rule, surface of semi-desert), zones of upward flows are filled, to a certain extent with the arid aerosol. This distinguishes them from less turbid zones of downward flows in the two-dimensional diagrams of laser sounding. Besides, the observed difference can be explained, in part, by the process of water vapor condensation on particles of atmospheric aerosol taking place in the upward flows.[3]

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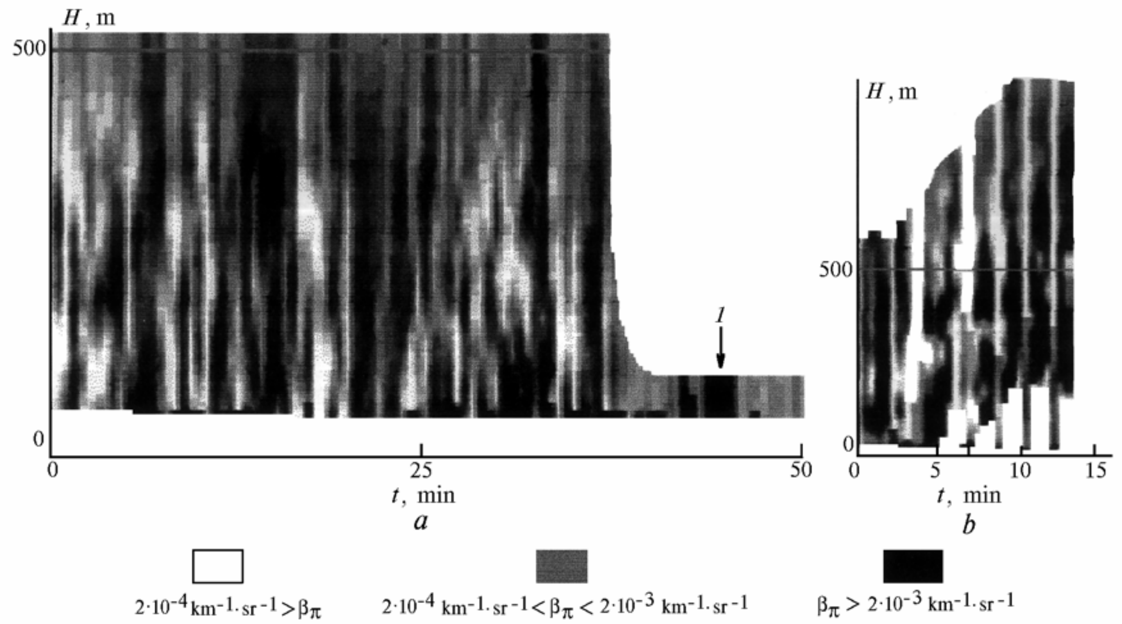

FIG. 1. Spatial distribution of the aerosol backscattering coefficient from the data of airborne laser sounding; Mashtak sands (1).

Groups of cells, each having horizontal size several times greater than the thickness of the boundary atmospheric layer, resemble the systems of Benar convective cells. The number of cells with the increased aerosol content, observed along the flight path in some selected groups, usually does not exceed 4–5 as follows from the data of our observation. This is indicative of the presence of a mesoscale intermittence in the convective boundary layer (with the scale about 25–60 km). Existence of the mesoscale structure in the convective boundary atmospheric layer has long been known[4] and is supported by some results of numerical modeling.[5]

It has recently been shown by the method of numerical modeling[6] that the weak altitude dependence of the horizontal size of convective cells is observed practically from the underlying surface up to the top of the convective boundary layer in the case of the mode of non-penetrating convection. It is the case, when the upward flows are incapable of penetrating the inversion layer, restricting the height of the convective boundary layer. From our data, similar situations are revealed quite frequently. In some cases, the size of upward convective cells increased with height, what is typical of the mode of penetrating convection.[6]

It should be noted that in the case presented in Fig. 1*b*, a semitransparent cloudiness (or haze) was visually observed from onboard the airplane in the lower part of the boundary atmospheric layer. According to modern views, this can take place under certain conditions in the convective boundary layer.[3]

Quasi-regular or quasi-periodic structures are not always observed in the convective boundary layer. Often non-ordered convective mode takes place. A relatively wide and irregular size distribution of convective cells (approximately from 2 to 6 km) is typical of such a mode. In this case it is worthwhile to use the spectral analysis of spatial distributions of aerosol characteristics in the convective boundary layer of the atmosphere along the horizontal paths. As an example, Fig. 2*a* presents the spectrum (*s* is the power spectral density) of spatial inhomogeneities of the aerosol backscattering coefficient β_π at the altitude about 350 m from the lidar sounding data on July 15, 1997. Inhomogeneities with scales about 8 and 40 km are clearly seen from the figure along with those, having horizontal scales about 2.5 and 4 km.

Inhomogeneities with the scale about 10–30 km were also observed in nephelometric measurements from onboard the airplane. Along with the "Benar" scale with the typical size about 3 km, nephelometric measurements have revealed horizontal inhomogeneities of aerosol density with smaller scales: a wide maximum with the center near 1.3 km.

Aerosol inhomogeneities with scales of hundreds of meters (nearly from 200 to 1000 m) are also pronounced. In this range of inhomogeneity size, mode intermittence is also observed. The synchronous measurements of temperature from onboard the airplane have demonstrated the peculiarities of the temperature inhomogeneity spectrum. The best agreement with the spectrum of scattering coefficient is observed in the mesoscale range (8–30 km). At smaller scales, temperature inhomogeneities proved to be relatively weak as compared to the aerosol ones. Quasi-sinusoidal behavior in the analyzed case of temperature inhomogeneities with scales about 8 km is likely indicative of the process of propagation of weakly pronounced internal gravity waves.

Figure 1*b* demonstrates the case, where a thick horizontally inhomogeneous cloud (or dense haze) was observed inside the boundary layer at altitudes from 200 to 700 m.

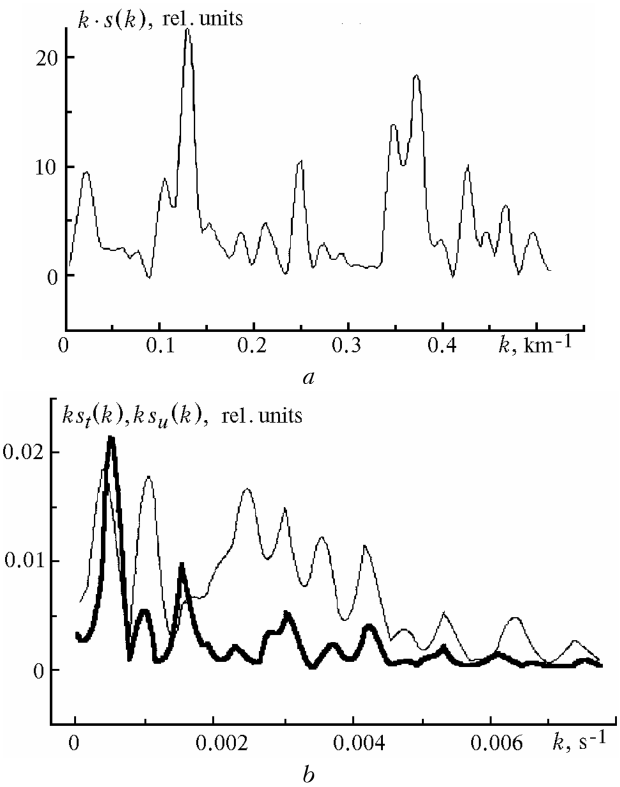

FIG. 2. Spectra of spatial inhomogeneities of backscattering coefficient in the atmospheric boundary layer (a) and time variations (b) of temperature (bold line) and wind velocity (thin line) in the near-ground atmospheric layer.

From the lidar sounding data on July 15, 1997, the most dense aerosol formations were found over the Mashtak sands (*1* in Fig. 1*a*). On this day, direct measurements of aerosol microstructure from onboard the airplane with the photoelectric particle counter confirmed the fact of aerosol carry-over from the territory of Mashtak sands (Fig. 3).

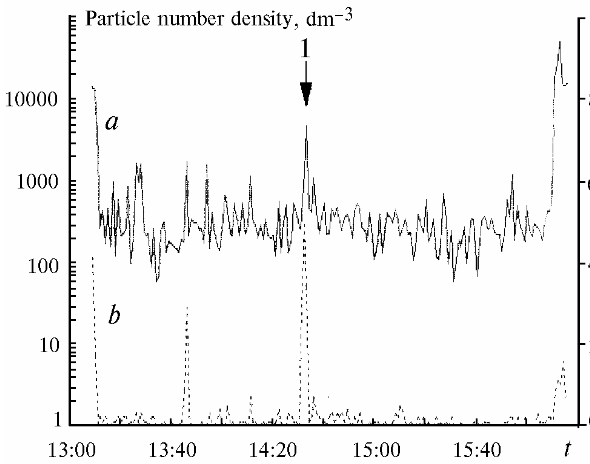

FIG. 3. Aerosol particle number density along the flight path over Kalmykiya on July 15, 1997, for particles with size larger than 0.3 μm *(a) and* 1 μm *(b); Mashtak sands (1).*

Measurements of characteristics of the near-ground aerosol in Mashtak sands have shown that the concentration of the submicron aerosol can reach 1000 μg/m^3 and higher. A sample of measurement results of the temporal behavior of mass concentration of the submicron aerosol under convective conditions using the nephelometric method is shown in Fig. 4.

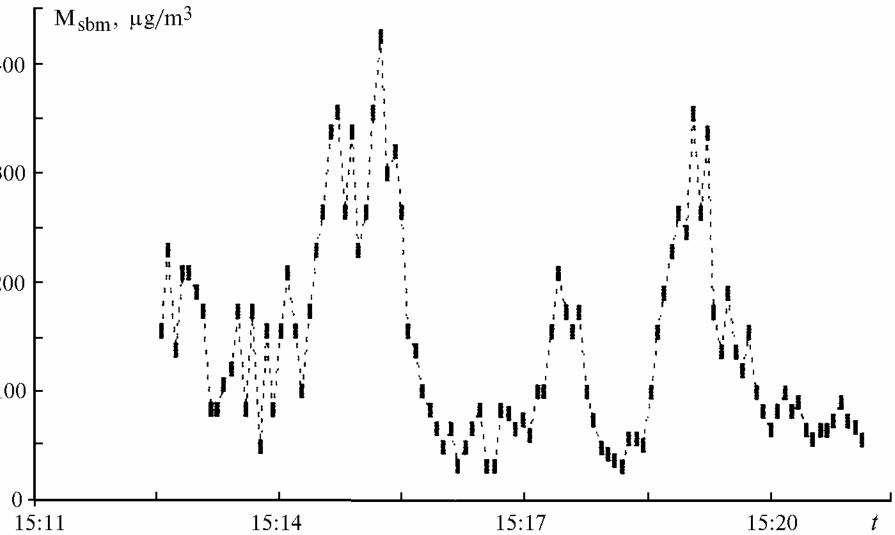

FIG. 4. An example of temporal variability of the mass concentration of the submicron aerosol in the ground atmospheric layer (Mashtak sands).

In particular, it turned out that the concentration of submicron aerosol varies (by several times) with the period about 100 s (by an order of magnitude). Strong fluctuations are indicative of the closeness of the aerosol source,[9] i.e. its local origin.

The synchronous wind velocity and temperature measurement with the temporal resolution about 1 s has shown that, in the case of the convective boundary layer, wind velocity and temperature variations (Fig. 2*b*) with pronounced maxima near 1000 s (by an order of magnitude) are observed in the ground atmospheric layer. At the mean wind velocity of 5 m/s in the boundary layer, it corresponds to horizontal inhomogeneities with the size about 5 km (convective cells).

The time spectrum of the absolute value of the wind velocity is far wider than the spectrum of temperature fluctuations (see Fig. 2*b*). Along with the "low-frequency" component, fluctuations with significantly shorter periods are pronounced. In particular, we have noticed that, in the convective mode, periods of wind strengthening about 1000 s long consist of a series of pronounced gusts 50–200 s long (on the average, about 100 s). This period agrees well with the observed duration of the strengthening periods of the submicron aerosol concentration.

Consequently, under convective conditions, "wind" carry-over of aerosol from the underlying surface (or from a thin atmospheric layer adjacent to the underlying surface) with the characteristic time scale of 100 s is observed in the ground atmospheric layer. In this case, the wind velocity reaches 5–6 m/s at the level of 4 m and 3 m/s at the level of 2 m.

It follows from the above-said that the results of measurements of aerosol parameters and meteorological elements in the ground and boundary atmospheric layers are indicative of a single convective mechanism controlling the behavior of the meteorological and aerosol parameters in the altitude range from 1 m to 1 km and even wider. "Generation" of aerosol by the underlying surface at deserted territories is modulated by wind gusts (vortices) with relatively long periods.

Thus, we have followed up the process of carry-over of aerosol from desert territories in the ground atmospheric layer and further aerosol transfer from the ground layer to the upper part of the boundary atmospheric layer.

It should be emphasized that the mechanism of aerosol carry-over (under conditions of convection) into the upper part of the boundary atmospheric layer differs significantly from the mechanism of vertical transfer of impurities in the mode of turbulent diffusion,[10] when transfer follows the direction of gradient of the impurity concentration. In this case, transfer is non-gradient (sometimes it is miscalled counter-gradient). Under certain conditions of convection, as well as advection or other ordered motion, transfer of an impurity is independent of its spatial resolution.

Turbulence determines the process of mixing under conditions of developed convection (mainly at small scales). The exceptions are the ground atmospheric layer, where turbulence plays a significant part in the process of aerosol carry-over from the underlying surface, and the upper part of the convective layer. It follows from our measurement data that the wind field $\mathbf{u} = \mathbf{u}(x, y, z, t)$, where x, y, z are the Cartesian coordinates and t is time, in the boundary atmospheric layer can be considered as a sum of three components (advective, convective, and turbulent ones)

$$\mathbf{u} = \mathbf{u}_{\mathrm{adv}} + \mathbf{u}_{\mathrm{conv}} + \mathbf{u}_{\mathrm{turb}}.$$

To construct the spatial distribution of $\mathbf{u}_{\mathrm{conv}}$, the results of numerical modeling of the dynamics of the boundary atmospheric layer[3,6] should be used.

At present considerable progress has been achieved in insight into the dynamics of the convective boundary layer of the atmosphere (see, for example, Refs. 6 and 11). However, there are no complete understanding and sufficiently complete models of this complex phenomenon as yet. Experimental and theoretical studies of the convective mode[1,6] have allowed the determination of the characteristic vertical velocities of upward and downward flows, as well as other parameters of convective flows in the boundary atmospheric layer.

Along with the data obtained in this paper, these data allows estimation of the amount of aerosol, which could be transferred during a relatively short time into the upper part of the boundary atmospheric layer. In this part, vertical velocities of upward motions become insignificant and the air that has risen spreads out in the under-inversion layer over the convective boundary layer. Having supposed that the area occupied by upward flows is about 40% of the total area,[6] we obtain the following expressions for the flow of aerosol mass transferred by convective motions, in $\mu g/(m^2 \cdot s)$:

$$\Phi = 0.4\, w\, M$$

where w is the average velocity of upward motions and M is the aerosol mass concentration in the lower part of the convective boundary layer (downward transfer of aerosol is neglected here). For the time t_0, a convective flow transfers the aerosol mass $M = \Phi\, t_0$ (per unit area). Having taken $w = 1$ m/s and $t_0 = 1000$ s, we obtain that, in a particular case at $M = 1000\ \mu g/m^3$, 0.4 g of aerosol is transferred to the altitude of 1 km through the area of 1 m^2. This corresponds to the vertical transfer rate about 1.5 ton/(km^2 hour).

The processes of convective transfer of aerosol from the ground atmospheric layer into the upper part of the boundary atmospheric layer were also observed earlier, including observations by the method of onboard laser sounding.[12] It should be noted that the process of convective purification of the atmospheric layer is also typical for big cities, especially in summer.

ACKNOWLEDGMENTS

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