Study of submicron aerosol uplift from the underlying surface

G.I. Gorchakov, B.M. Koprov, and K.A. Shukurov

A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow

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Synchronous measurements of fluctuating meteorological parameters and the submicron aerosol number concentration, made near the Aral Sea, are analyzed. It is shown that aerosol uplift from the surface in the form of "spikes" is associated with wind squalls, or with periods of air temperature rises in the atmospheric boundary layer. We have analyzed power spectra of fluctuations of the aerosol concentration, air temperature, and longitudinal component of the wind velocity.

Introduction

The desertification process is one of the main factors controlling global environmental change. In arid and semiarid territories, desertification depends crucially on aerosol uplift from the underlying surface and subsequent aerosol transport in the atmosphere. In addition to dust storms, uplift of aerosol, including submicron-size particulates, frequently occurs during surface heating by shortwave radiation. The complex mechanism of this phenomenon is still far from being completely understood.

The processes of aerosol uplift and dust/salt transport have been studied at the Institute of Atmospheric Physics for many years. With support from the ISRC (through Grant No. 95–035 to Academician G.S. Golitsyn), the RFBR (through Grant No. 95–5–66170 to G.I. Gorchakov) and other agencies, this effort has been greatly expanded. In 1995–1997, in collaboration with Karpov SRIPC (A.V. Andronova, V.M. Minashkin, et al.), the Institute of Experimental Meteorology (V.V. Smirnov et al.), and other organizations, we performed integrated ground-based and airborne observations and identified, during the fall of 1998, some important features of the process of thermal-convective aerosol uplift from the Kalmyk desert territory into the atmospheric boundary layer. Later on, this work was continued in the desert region near the Aral Sea as part of a joint Russian-Kazakh expedition. In the present paper, we discuss results of synchronous measurements of variations of aerosol concentration and turbulence characteristics in the atmospheric boundary layer; the measurements were made near the Aral Sea in September 1998.

1. Fluctuations of aerosol concentration

The experience accumulated in studies of diurnal transformations of atmospheric aerosol indicates that fundamental features of most aerosol transformation processes cannot be adequately understood without appropriate data on short-period variations of aerosol optical and microphysical parameters. To study the statistical characteristics of short-period variations of the scattering coefficient, we developed (a) a fast-response flow nephelometer that has a time constant of 0.1–1 s in the signal recording mode and which we used, in particular, in airborne sensing of arid aerosol in the atmospheric boundary layer over Kalmykia in 1996–1997[2,4]; and (b) a high-speed computer-aided aerosol particle counter that has a computer-controlled sampling rate of between 1 s and a few minutes in particle size distribution measurements. Based on an AZ–6 photoelectric counter, the fast particle counter allows one to measure particle size distributions in the diameter range from 0.3 to roughly 2 μm. The practically feasible size range is determined by particle concentration, shape of the particle size spectrum, and sample size since it must be larger than the counter sensitivity limit determined by the admissible sampling error.

The particle counter was field-tested and generally demonstrated to provide reliable measurements of submicron-size particles when the sampling time is on the order of 1 min. At the same time, the number concentration of particles roughly 0.3 μm in size can be determined within 1 s. In the summer of 1998, from onboard a low-tonnage research vessel we measured the time variations of the particle size distribution in the atmospheric boundary layer over the Caspian Sea; the measurements with a time resolution of 1 min revealed[5] different fluctuation modes of the aerosol microstructure. In particular, we detected almost periodic variations of the aerosol concentration in the southeastern Caspian Sea.[5]

Data on short-period variations of aerosol properties are especially needed to study aerosol uplift from the underlying surface and its subsequent transport in the turbulent atmosphere. Despite their definite advantages in terms of high accuracy and sensitivity, nephelometric measurements are seriously deficient in that the effective aerosol particle sizes they provide are highly uncertain. So, the high-speed particle counter was chosen over the nephelometer to study aerosol uplift.

During the Aral expedition in September 1998, particle size distributions were measured with a time resolution of 1 s. Here we discuss only measurements of integrated or total particle concentrations in the submicron size range, which is close to the differential number concentration of particles in the range from 0.3 to 0.5 μm. Aerosol sampling was performed using a short air intake at a height of about 2 m. The landscape was a flat terrain with long (about 10-m) flat sandy barkhans nearly 1 m in height.

Analysis of the number density fluctuations in the near-Aral region[6,7] revealed substantial differences in the character of submicron aerosol uplift from the underlying surface. Aerosol generation is found to be quasicontinuous when wind speeds at a height of 2 m exceed 8–10 m/s, whereas at lower wind speeds submicron aerosol uplift

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from the underlying surface occurs in the form of separate emissions or spikes about 100-s long, or as a succession of such spikes.

As an example, Fig. 1 shows the time dependence of the particle concentration N that we measured on September 22, 1998, for 1500 s (curve *1*). In this time period, we recorded four aerosol spikes ranging in duration from about 50 to 100 s. Typically, the aerosol spikes had steep leading and trailing edges, suggesting a nonlinear mechanism of particle generation.

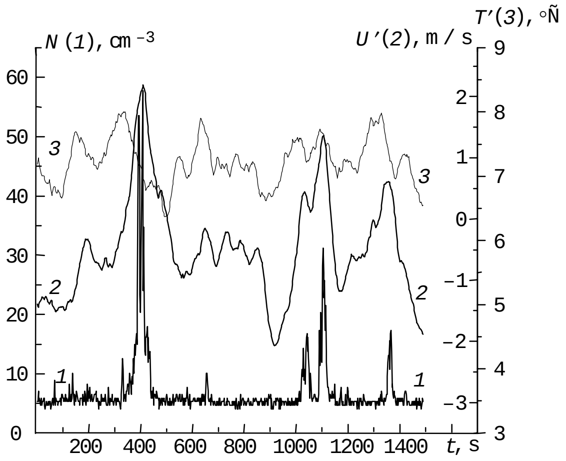
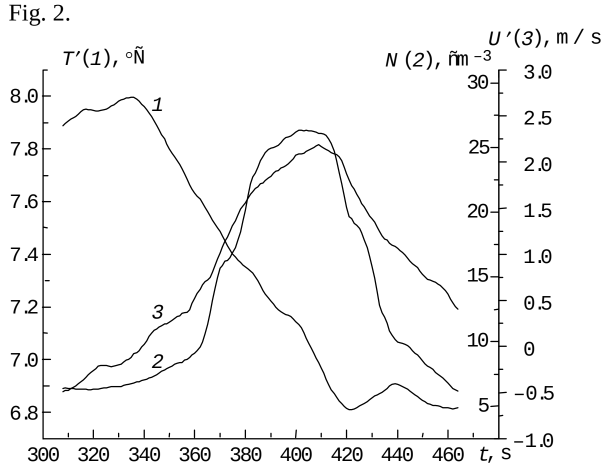


Fig. 1. Example of synchronous measurements in the near-Aral region on September 22, 1998; the graph shows the particle number concentration N (curve *1*), fluctuations of the longitudinal wind component U' (curve *2*), and fluctuations of the temperature T' (curve *3*).

Generally, the aerosol particle concentration and meteorological parameters in the uplift zone widely vary in time. Therefore, it is expedient to analyze the aerosol uplift process separately in the low- and high-frequency ranges of variations of the parameters studied. To identify the low-frequency component of individual events containing aerosol spikes, we calculated 50-s moving averages of the measured aerosol concentration and meteorological parameters. An example of a smoothed spike is shown in Fig. 2.



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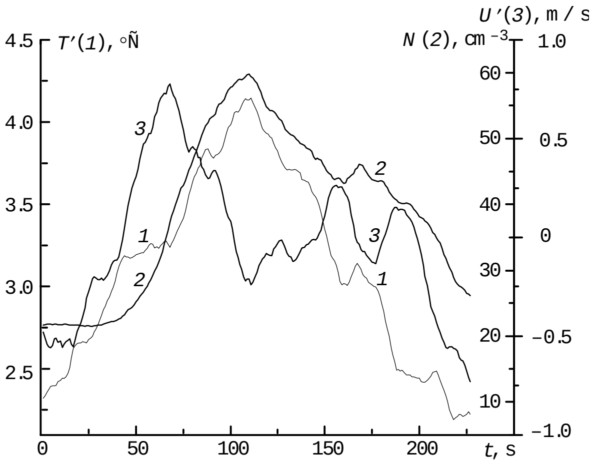

b

Fig. 2. Example of the smoothed (using a 50-s moving average) time dependence of particle number concentration N (curve *2*), smoothed fluctuations of the air temperature T' (curve *1*), and longitudinal component of the wind speed U' (curve *3*), measured (*a*) during the aerosol spike on September 20, 1998 and (*b*) on September 22, 1998.

We note that the fluctuations of the air temperature and longitudinal component of the wind speed, plotted in Fig. 2, represent deviations from their respective mean values on time scales substantially longer than those indicated in Fig. 2. Partly for this reason, the T' values on the y axis turned out to be only positive in value.

An important characteristic of an aerosol spike is the regime of fluctuations of the particle concentration N. We analyzed short-period or "high-frequency" (1 to ~100-s) variations of the concentration both during periods of aerosol spikes and without. It was found that, during a spike, the level of number density fluctuations increases by about an order of magnitude or greater. Figure 3 shows approximate power spectra of fluctuations S_N of the particle number density we measured on September 22, 1998, during (curve *1*) and just before (curve *4*) one of the aerosol spikes shown in Fig. 2*b*. The slope of the log–log plot of S_N as a function of f (where f is frequency) is 1.24 at the time of the spike and 0.98 before it.

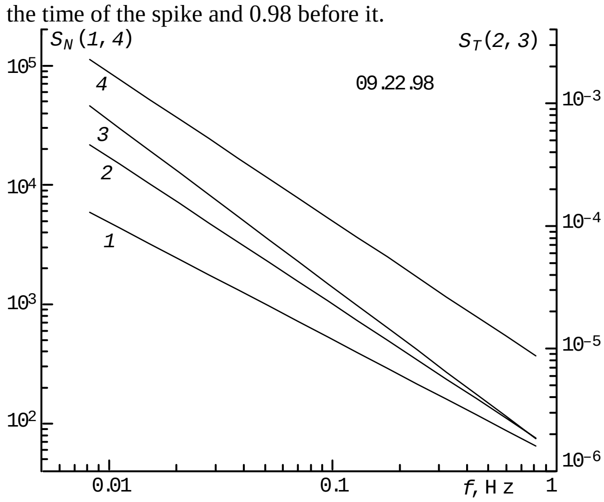

Fig. 3. Approximate power spectra of fluctuations of the particle number concentration S_N (curves *1* and *4*) and fluctuations of the

air temperature S_T (curves *2* and *3*) measured during an aerosol spike (curves *3* and *4*) and prior to it (curves *1* and *2*).

A study of the finer structure of the temporal variations of the aerosol number density goes beyond the scope of the present paper.

2. Fluctuations of air temperature and wind velocity components

Spike-like uplift of aerosol from the underlying surface is found to occur under convective flow conditions.[4,7] Using the method of lidar-nephelometric airborne sensing, we studied the aerosol spatial distribution in the atmospheric boundary layer over Kalmykia[4] and detected horizontal inhomogeneities on spatial scales from tens of meters to tens of kilometers. These inhomogeneities are closely related to various convective regimes forming in the atmospheric boundary layer.[2,4] Measurements of fluctuations of the air temperature and horizontal components of the wind velocity in Kalmykia (Mashtak sands) have shown that in the atmospheric boundary layer there exist distinct variations of meteorological parameters on time scales of ~ 1000 s, probably associated with passage over the measurement sites of upward and downward moving convective cells with horizontal sizes of about several kilometers, and with fluctuations on smaller time scales of about 100 s. *In situ* measurements (with a time resolution of 1 s under convective conditions) revealed substatial variations of the atmospheric lapse rate,[7] both in absolute value and in sign, suggesting a transient character of changes in the stability of the atmospheric boundary layer.

In the Aral 1998 expedition, fluctuations of wind speed components were sampled at a rate of about 30 Hz using a three-component anemometer, and fluctuations of air temperature were sampled at the same rate using fast-response thermometers.[8] In interpolations of time variations of meteorological characteristics, we will consider separately their "low-frequency" (smoothed) and "high-frequency" components.

Figure 1 shows examples of smoothed (over a 50-s time window) fluctuations of the longitudinal component U of the wind velocity (curve *2*) and of the temperature T (curve *3*) inferred from the September 22, 1998 measurements in the near-Aral region. For a mean wind velocity of about 5 m/s, the amplitude of the low-frequency variations (with periods as long as 100–300 s) is approximately ± 2 m/s. The amplitude of the low-frequency air-temperature variations (with periods as long as 100–200 s) is approximately $\pm(0.7–0.8)$°C. It is noteworthy that the observed low-frequency air-temperature variations differ considerably from those of the longitudinal component of wind velocity. It is also important that, in addition to long periods of wind strengthening, there also occur quite long lasting positive temperature anomalies with amplitude of about 1° in the atmospheric boundary layer. We will nominally refer to these positive temperature anomalies as "thermics". Also, the long-lasting ("low-frequency") anomalies of the air temperature and longitudinal components of the wind velocity are clearly discernible in Fig. 2.

Now let us briefly discuss how "low-" and "high-frequency" fluctuations of the air temperature and the longitudinal component of the wind velocity are related. Figure 3 shows approximate power spectra of fluctuations of air temperature T (curves *2* and *3*) inferred from measurements in the near-Aral region; the measurements were made on September 22, 1998 during the aerosol spike (curve *3*) illustrated in Fig. 2, and before it (curve *2*). Interestingly, the spectral power of air temperature fluctuations before and during the aerosol spike is almost the same.

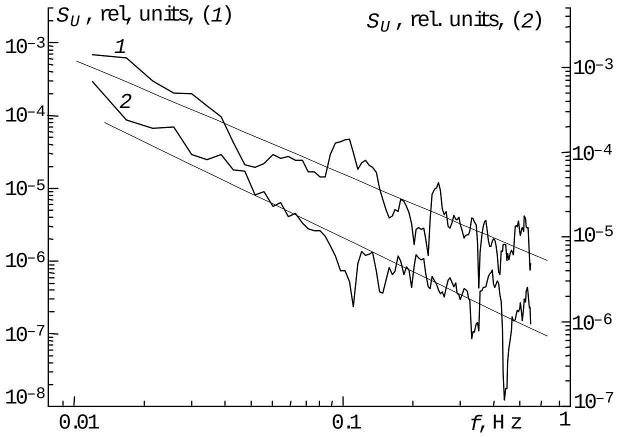

Fig. 4. Power spectra of fluctuations of the longitudinal wind velocity component S_U and linear fits to them, inferred from measurements made during the aerosol spike on September 20, 1998 (curve *1*) and before it (curve *2*).

For the aerosol spike on September 20, 1998 (shown in Fig. 2*a*), we calculated the power spectrum of fluctuations of the longitudinal wind velocity component S_U (curve *1* in Fig. 4). The straight line is a fit to the data. Comparison shows that the fluctuations of the longitudinal wind velocity component S_U have much less spectral power before the aerosol spike than during it. Also, there is a change in the spectral exponent, from –1.20 before the spike to –1.36 during it.

Analysis of the other wind velocity components goes beyond the scope of this paper.

3. Influence of fluctuations of wind velocity and air temperature on aerosol uplift rate

We have analyzed the results of synchronous nephelometric measurements of the scattering coefficient and measurements of the atmospheric lapse rate and wind velocity variations made in Kalmykia in the summer of 1997; it was found that a correlation exists between spikes in the aerosol concentration in the atmospheric boundary layer and wind squalls (i.e., increases in the horizontal wind velocity components). The aerosol spikes and wind squalls lasted roughly 100 s.[2]

Synchronous measurements of fluctuations of the aerosol number concentration and meteorological parameters in the near-Aral region during the fall of 1998 confirmed this finding. Figure 1 compares measurements of the aerosol number concentration N with those of smoothed fluctuations of the air temperature T' and the longitudinal wind velocity component U'. It is plainly evident that the aerosol spikes coincide in time with the periods of wind strengthening. Note the temporal correspondence between the second and third spikes, on the one hand, and the second and third wind squalls, on the other[7]; in Fig. 1, these two wind squalls overlap in time, because the 50-s moving average is too long for this case. In Fig. 1, there is an obvious mismatch between the low-frequency air temperature fluctuations and the temporal variations of the aerosol concentration. The only exception occurs for the fourth spike, before which, indeed, it is possible to identify a period lasting about 150-s of increased air temperature. The fact that variations of the aerosol number concentration and the longitudinal wind velocity component during aerosol spikes match very closely is most clearly seen from a comparison of smoothed time dependences of the aerosol number concentration with those of the wind velocity components (see Fig. 2*a*).

Subsequent analysis has shown, however, that the aerosol spikes do not always coincide with periods of wind strengthening or wind squalls.

In many cases, the aerosol spikes were attributed temporally to episodes of an air temperature rise and spatially to (horizontally) extended zones of increased air temperature ("thermics"), as was, for example, the case on the day illustrated in Fig. 2*b* (AT episode). Obviously, this type of aerosol uplift differs radically from that mentioned above (AU episode).

In the above discussion it was shown that a characteristic feature of wind squalls is a significant increase in the power level of the longitudinal wind velocity fluctuations. These fluctuations can have a considerable influence on the development of aerosol spikes when a wind squall acts on the underlying surface.[9]

In contrast, air temperature fluctuations, presented in Fig. 3, do not change significantly between periods of increased air temperature and the ensuing aerosol spikes, and those preceding the aerosol spikes. It is noteworthy that the power spectra of air temperature fluctuations differ significantly from those of the submicron aerosol concentration.

We compared our results with measurements under conditions in which no aerosol uplift from the underlying surface was expected.[10] Some differences between the power spectra of the aerosol and wind velocity fluctuations were found; however, too few data have been published to date to draw any definite geophysical conclusions about this.

Conclusion

It has been shown that aerosol uplift from the underlying surface, occurring in the form of aerosol spikes on time scales of about 100 s, can be associated with wind squalls on about the same time scale. Otherwise, the aerosol spikes are attributed to increases of air temperature ("thermics") in the atmospheric boundary layer, again occurring on about same time scales as the aerosol spikes.

The spectral power of the wind velocity fluctuations is much larger during aerosol spikes than under non-spike conditions, whereas air-temperature fluctuations have nearly the same spectral power both in the "thermics" and outside them.

Acknowledgments

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