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Eclipse Effects in the Atmospheric Boundary Layer

G. I. Gorchakov[a], E. N. Kadygrov[b], Z. V. Kortunova[c], A. A. Isakov[a], A. V. Karpov[a], V. M. Kopeikin[a], and E. A. Miller[b]

[a] *Oboukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia*
e-mail: gengor@ifaran.ru

[b] *Central Aerological Observatory, Pervomaiskaya ul. 3, Dolgoprudnyi, Moscow oblast, 141700 Russia*

[c] *FGU Pyatigorsk State Research Institute of Roszdrav Health Resort Treatment, pr. Kirova 30, Pyatigorsk, 357500 Russia*

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Abstract—The influence of a solar eclipse on solar-radiation fluxes, meteorological parameters, turbulence characteristics, and vertical temperature profiles in the atmospheric boundary layer is analyzed. Air-temperature variations caused by an eclipse and time delays of these variations with respect to the onset of the total-eclipse phase in the atmospheric surface and boundary layers are determined. The influence of a solar eclipse on the turbulent kinetic energy, turbulent heat flux, and variance and spectral density of the power of air-temperature pulsations are estimated. Variations in aerosol parameters and concentrations of light ions during a total solar eclipse are discussed.

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INTRODUCTION

In spite of the regularity of solar eclipses [1], their influence on processes in the atmospheric boundary layer (ABL), including the ABL air-temperature distribution and turbulence regime, have not been sufficiently studied, The influence of solar eclipses on atmospheric aerosol and electric characteristics of the atmospheric surface layer (ASL) remains virtually unexplored. Within this study, we experimentally investigated the influence of a solar eclipse on solar-radiation fluxes, meteorological parameters of the ASL, and turbulent pulsations of wind-velocity components and air temperature in Kislovodsk during the total solar eclipse of March 29, 2006. Additionally, we investigated the influence of the solar eclipse on vertical profiles of air temperature in the 0–600 m layer, microphysical parameters of aerosol, and concentrations of atmospheric ions. Eclipse effects are compared to the corresponding intradiurnal variations in the measured characteristics.

TOTAL SOLAR ECLIPSE OF MARCH 29, 2006, IN KISLOVODSK

In the territory of Russia, the first total eclipse of the 21st century occurred on March 29, 2006. The visibility band of the total solar eclipse passed from the eastern coast of Brazil, across the Atlantic Ocean, western and northern Africa, including Nigeria, Ghana, and Libya, and farther across the Mediterranean Sea, Turkey, Greece, and the Black Sea. In Russia, the band of the total solar eclipse passed through the North Caucasus and Caspian region and later through the Altai territory. The band of the total solar eclipse in Kislovodsk is shown in Fig. 1. The partial solar eclipse was seen in Europe, in the major parts of Asia and the Arctic, and at the eastern coast of South America. In Russia, the partial eclipse was observed in European Russia and in Western and Eastern Siberia.

In Kislovodsk, the solar eclipse of March 29, 2006, began at 14:03 LT and ceased at 16:29 LT. The total-

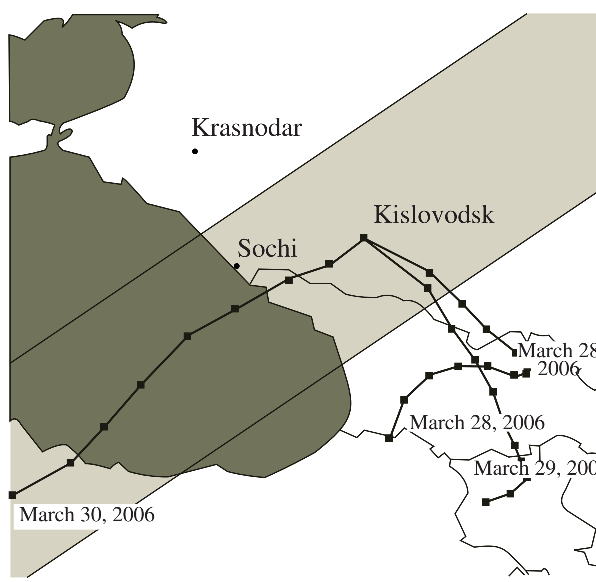

Fig. 1. Schematic map of the total solar eclipse of March 29, 2006, in the Kislovodsk area and back trajectories of air-mass transfer.

eclipse phase continued for about 2.5 min, from 15:16:31 to 15:19:03.

The meteorological conditions in Kislovodsk on March 29, 2006, were favorable for observation of the eclipse. According to data of the local meteorological agency, a continental moderate air mass with a neutral stratification at the southwestern periphery of an anticyclone prevailed in Kislovodsk during that day. The advection of heat was absent. Optically thin cirrus clouds with an amount of 1–2 were observed over Kislovodsk at noon, approximately one hour before the beginning of the eclipse. Additionally, cumulus clouds with an amount of no more than 2 were present near the horizon before noon. By the beginning of the total eclipse, rare clouds (cirrus and altocumulus) completely disappeared from the visibility zone. On March 29, 2006, there was no precipitation in Kislovodsk. A relatively weak southerly and southeasterly wind (see below) was observed in Kislovodsk during this day. The back trajectories of air-mass transport at 850 mbar are also presented in Fig. 1 for March 29–30, 2006. The time interval between the neighboring points on the trajectories is 6 h. It is seen that the air mass that moved from the Main Caucasus Range was in the area of Kislovodsk on the day of eclipse.

The front of the atmospheric-pressure ridge was located over Kislovodsk at 500 mbar, and the weak-gradient field of atmospheric pressure was at 700 and 850 mbar. Jet streams and atmospheric fronts were not observed. The weather during the days before and after the eclipse (March 28 and 30, 2006) did not differ substantially from the weather on March 29, 2006.

COMPLEX INVESTIGATION OF THE INFLUENCE OF THE SOLAR ECLIPSE ON CHARACTERISTICS OF THE LOWER ATMOSPHERE

Complex experiments aimed at revealing eclipse effects in the ABL were carried out in Kislovodsk during the last third of March 2006. Instruments were mounted at the meteorological station of the Pyatigorsk Roszdrav State Research Institute of Health Resort Treatment (900 m above sea level). Aerosol parameters and the concentrations of atmospheric ions were also measured in the area of the Scientific Station of the Institute of Atmospheric Physics in Kislovodsk (ul. Gagarina).

A decrease in radiation flux is the primary manifestation of a solar eclipse [3]. To control the radiation regime of the atmosphere, we measured the total flux of shortwave radiation (spectral range 300–3000 nm) with a CNRI radiometer–balance gauge (net radiometer) (Kipp and Zonen, Holland) with an error of ±10 W/m^2. Detailed information about this instrument is given at the site of company-manufacturer (www.kippzonen.com).

It should be expected that changes in the flux of the incident solar radiation during the eclipse comparatively rapidly manifest themselves in changes in the temperatures of the underlying surface and ASL [3–5]. Variations in the air temperature and other meteorological parameters of the ASL were controlled with the use of a Meteo-2M acoustic meteorological station [6], developed at the Institute of Atmospheric Optics (Tomsk). The Meteo-2M automatic meteorological station records three components of the wind velocity (error ±0.1 m/s), temperature (error ±0.3°C), and relative air humidity (error ±5%). Owing to a relatively high time resolution (0.1 s), the meteorological station makes it possible to measure turbulent pulsations of the wind-velocity components and air temperature.

To measure the vertical profile of air temperature in the ABL, we used an MTP profiler (SHF radiometer) [7], developed at the Central Aerological Observatory (Dolgoprudnyi, Moscow oblast). The measurements were conducted in the layer from 0 to 600 m above the underlying surface with a step in height of 50 m and a time resolution of 5 min. The error of temperature measurements did not exceed ±0.3°C.

Since the lowermost atmospheric layers must cool the most rapidly, the eclipse must increase the stability of these layers and, consequently, manifest itself through changes in the turbulence regime. Turbulence parameters [8] were determined from measurements of turbulent pulsations of the three wind-velocity components and air temperature for 15-min time intervals. In some cases, calculations were performed for shorter or longer time intervals.

We expected that, at a constant absolute humidity, temperature variations in a homogeneous air mass must change the relative air humidity and in turn change the water content in aerosol particles; consequently, temperature variations must manifest themselves through changes in the size of particles and their optical properties. During the eclipse experiment, we measured the scattering coefficient (for an optical wavelength of 550 nm) with a miniature flow-type nephelometer developed at the Institute of Atmospheric Physics of the Russian Academy of Sciences. The determination error of the scattering coefficient is about ±10%, and the time resolution is 1 s. Additionally, we measured (15-s time averaging) particle size distributions in the range from 0.2 to 1.5 μm (measurement error of the number concentration is ±25%).

The variations in microphysical aerosol parameters caused by a solar eclipse can affect electric characteristics of the ASL and, in particular, change concentrations of atmospheric ions [9]. During the Kislovodsk experiment, we measured concentrations of negative and positive light ions (mobilities more than 0.4 cm^2 V^{-1} s^{-1}) with SIGMA-1 and SIGMA-2 ion counters (30% error of a single measurement; 1.5-s intervals of measurements). All of the measurements

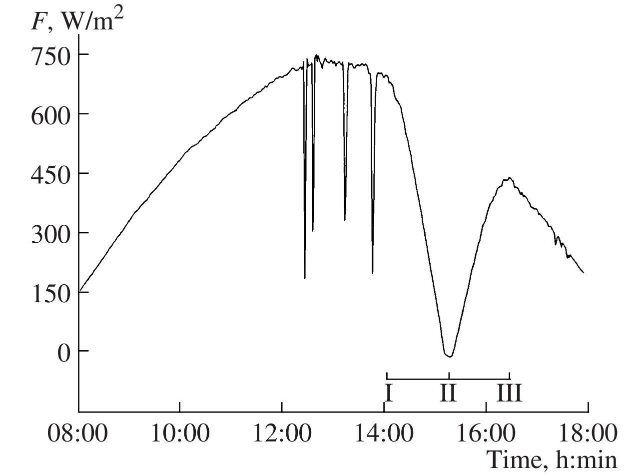

Fig. 2. Variations in the flux of total shortwave solar radiation in Kislovodsk on March 29, 2006 (I, III, and II are the beginning, termination, and totality of the eclipse, respectively).

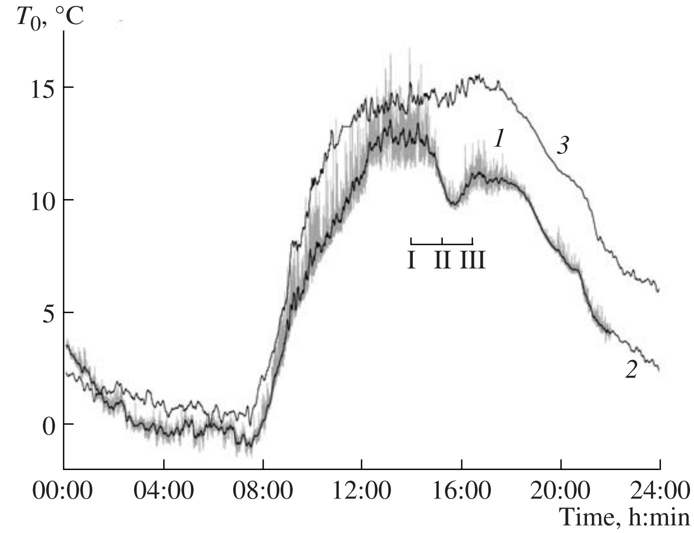

Fig. 3. (*1*) Temporal variability of the surface temperature in Kislovodsk on March 29, 2006 (1-s time averaging), and smoothed variations in the surface temperature (5-min time averaging) on (*2*) March 29, 2006, and (*3*) March 30, 2006. I, III, and II mark the beginning, termination, and totality of the eclipse, respectively.

listed above were conducted with the use of automatic recording systems.

DISCUSSION OF EXPERIMENTAL RESULTS

Fluxes of solar radiation. The solar eclipse most clearly manifested itself in changes in the flux of total (direct and scattered) shortwave solar radiation F (Fig. 2). The beginning (I), termination (III), and totality (II) of the eclipse, respectively, are marked in Fig. 2 and the next figures. In the totality period, the flux F dropped to zero within the accuracy of measurements. The rate of changes in the solar-radiation flux $F^{-1}dF/dt$, where t is time, attained about 12 min^{-1}. Rare clouds in the near-noon period led to short-term decreases in the shortwave solar radiation (Fig. 2) but did not affect the radiation regime of the atmosphere during the day of the solar eclipse.

The sum of solar radiation (in J/m^2) at the underlying surface over the time period from t_1 to t_2 is

$$\Phi_{12} = \Phi(t_1, t_2) = \int_{t_1}^{t_2} F(t)dt.$$

The solar eclipse decreases the sum Φ_0 accumulated over the day by the quantity $\Delta\Phi$; therefore, the energy action of the solar eclipse can be characterized by a ratio of $\eta = \Delta\Phi/\Phi_0$. Calculations showed that this ratio was about 10–12%.

Meteorological parameters of the ASL. Owing to a decrease in the underlying-surface illuminance under the influence of the solar eclipse, the thermal regime of the lower atmospheric layers changes as well. The diurnal variation of the surface-air temperature T_0 during the day of the eclipse is shown in Fig. 3 with a time resolutions of 1 s (curve *1*) and 5 s (curve *2*). The diurnal variation of the surface temperature during the next day after the eclipse (March 30, 2006) is also shown in Fig. 3 (curve *3*) for comparison (5-min time averaging). The averaged values of T_0 and the absolute value of the wind-velocity horizontal component V (m/s) in the ASL for some time periods are given in the table. The tabulated data related to the time period from 13:35 to 14:15 will be regarded as the data preceding the eclipse ("preeclipse" data). The minimum air temperature (Fig. 3) was fixed about 20 min after the middle of the total eclipse. During total eclipse (for the 3-min time interval from 15:16 to 15:19), the surface temperature exceeded the minimum temperature by about 1.5°C. According to the data of measurements with the Meteo-2M acoustic meteorological station, the decrease ΔT_0 in the surface temperature T_0 caused by the eclipse was about 3°C.

Considerable variations in the magnitude of the horizontal wind velocity V were observed on the day of the eclipse. Therefore, it was difficult to separate the possible V variations caused by the eclipse from the low-frequency variations in the wind velocity that were due to other factors.

The wind direction in Kislovodsk changed before the eclipse by 90° in the period from 12:20 to 12:30 and by another 30° at 14:30. Apparently, these wind changes have no direct relation to the eclipse. During

Meteorological elements and turbulence parameters in the atmospheric surface layer (Kislovodsk, March 29, 2006)

Time	T_0, °C	V, m/s	E, m^2/s^2	σ_w^2, m^2/s^2	σ_T^2, (°C)^2	R, W/m^2
12:20–12:50	12.5	1.8	2.90	0.60	0.33	110
13:35–14:15	12.9	2.5	3.70	0.68	0.42	170
14:30–15:00	12.5	3.0	2.50	0.50	0.25	160
15:16–15:19	11.4	2.5	2.00	0.43	0.14	56
15:30–16:15	10.0	2.4	1.45	0.30	0.04	50
16:15–16:45	10.9	2.1	1.50	0.37	0.11	100
17:35–18:05	10.9	2.9	1.70	0.47	0.04	65

Note: T_0 is the surface temperature; V is the wind velocity; E is the turbulent kinetic energy; R is the turbulent heat flux; and σ_w^2 and σ_T^2 are the variances of pulsations of the wind-velocity vertical component and the air temperature, respectively.

the solar eclipse, the relative air humidity increased by about 10–15%, but it was no greater than 55%.

Vertical profiles of the air temperature. A noticeable decrease in the air temperature during the eclipse was observed at all heights in the 0–600 m layer. Such detailed measurements of temperature profiles in the ABL during the solar eclipse have not been conducted previously. Figure 4 shows the diurnal variations of the air temperature measured on March 29, 2006, with the MTP-5 profiler in the surface layer (curve *1*) and at heights of 100 (curve *2*), 200 (curve *3*), 400 (curve *4*), and 600 m (curve *5*). According to the MTP-5 data, the air temperature decreased in the ASL by 3.9°C and at 600 m by 2°C. The difference between the ΔT_0 values obtained with the acoustic meteorological station and with the microwave profiler can be explained by the fact that the air volumes in which the temperature T_0 was determined by these instruments were located at a distance of about 50 m from one another and by specific features of the spatial structure of upward and downward flows in the city, which has a complex orography and dense costruction. On average, the temperature decrease ΔT_0 in the ASL was 3.5 ± 0.5°C. Note that with increasing height, the time when the minimum air temperature is established increases with respect to the time when the solar-radiation flux F is minimum at 20 min in the surface layer to 40 min at heights of 200 m or more (curve *6* in Fig. 4). Unfortunately, the height variation of the time delay could not been determined exactly because of comparatively large irregular variations in the air temperature.

More detailed information on the influence of the solar eclipse on the thermal regime of the ABL can be retrieved from analysis of the temporal variability of the vertical temperature profile during the eclipse and from comparison of these changes to the diurnal variability of the vertical profile of air temperature. Figure 5 shows the vertical profiles of air temperature in the 0–600 m layer over Kislovodsk during the day of eclipse for different time moments (5-min averaging): at the end of the night at 05:00 (curve *1*), in the morning at 08:30 (curve *2*), in the daytime before the eclipse at 13:30 (curve *3*), in the period of maximum temperature decrease (curve *4*), after the eclipse at 17:35 (curve *5*), and in the evening at 21:15 (curve *6*). For comparison with the observed temperature profiles, this figure likewise shows the dry adiabat (curve *7*) with the temperature gradient $\gamma = 0.98$°C/100 m; the temperature profile for the regime of autoconvection (curve *8*) [10], when the air density does not depend on height (vertical temperature gradient 3.42°C/100 m); the mean temperature gradient for the troposphere 0.65°C/100 m (curve *9*) [10]; and the isothermal profile (curve *10*).

Before the eclipse, developed convection took place in the lower 100-m layer (curve *3* in Fig. 5), and

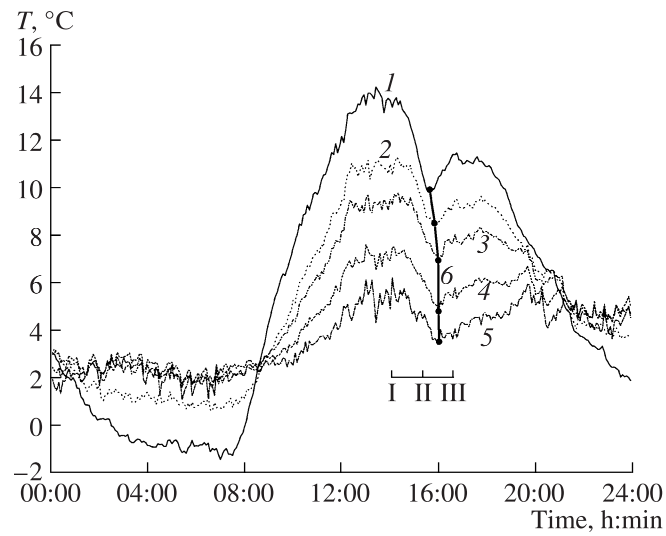

Fig. 4. Air-temperature variations on March 29, 2006, in Kislovodsk in the atmospheric boundary layer at the levels (*1*) 0, (*2*) 100, (*3*) 200, (*4*) 400, and (*5*) 600 m. Line *6* connects the points of minimum temperatures; I, III, and II are the beginning, termination, and totality of the eclipse, respectively.

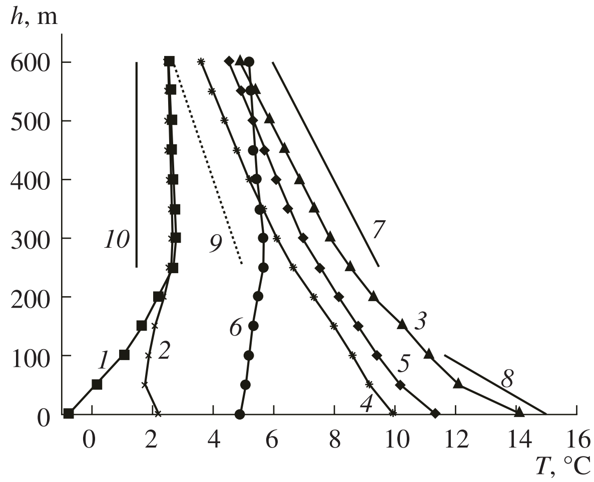

Fig. 5. Vertical profiles of the air temperature on March 29, 2006, in Kislovodsk: in the morning at (*1*) 05:00 and (*2*) 08:30, in the daytime before the eclipse at (*3*) 13:30, (*4*) in the period of the maximum decrease in the surface temperature, (*5*) after the eclipse at 17:35 and (*6*) in the evening at 21:25. Line (*7*) is the dry adiabat); (*8*) and (*10*) correspond to the regimes of autoconvection and isothermy, respectively; and (*9*) is the profile for the case of the mean gradient in the troposphere.

at heights from 300 to 600 m, the vertical temperature gradient (1.0°C/100 m) was close to the dry-adiabatic gradient. During the temperature minimum caused by the eclipse (curve *4* in Fig. 5), the stability of the lower 200-m layer increased noticeably and the vertical gradient decreased to 1.3°C/100 m. In the upper layers (300–600 m), stability growth was not large (temperature gradient of 0.85°C/100 m). After the eclipse (curve *5* in Fig. 5), the instability again began to develop in the lower part of the ABL. However, the nearing onset of evening twilight sharply increased the stability of the entire boundary layer up to isothermy in the layer 250–600 m and a mild inversion in the lower part of the boundary layer (curve *6* in Fig. 5). As follows from Fig. 5, the degree of diurnal variability of the vertical temperature profiles is still larger: inversions (up to –1.8°C/100 m) are formed at night in the lower 100-m part of the boundary layer (curve *1* in Fig. 5). Thus, it is seen that the degree of diurnal variability of the temperature profiles is much larger than their variability caused by the solar eclipse.

Regime of turbulence. The increase in the boundary-layer stability during the solar eclipse noticeably changed the turbulence regime in the ASL. On the day of the eclipse, the pulsations (deviations from means) u', v', and w' of the longitudinal, transverse, and vertical wind-velocity components u, v, and w, as well as the air-temperature pulsations T', were measured with a time resolution of 0.1 s by using the Meteo-2M acoustic meteorological station. The following parameters were determined for 15-min observation intervals: turbulence parameters [8], including the turbulent kinetic energy $E = 0.5\,[(u')^2 + (v')^2 + (w')^2]$; the variances [11] w' and T' of turbulent pulsations of the vertical velocity component w and the air temperature T, respectively; as well as the turbulent heat flux $R = \rho c_p \overline{w'T'}$ (W/m^2), where the overbar means time averaging, ρ is the air density, and c_p is the air heat capacity at constant pressure. The values of the turbulence parameters listed above for seven periods of March 29, 2006, including total eclipse, are presented in the table. Note that the turbulence parameters measured in the period from 13:35 to 14:15 are regarded as preeclipse parameters (table).

The turbulence parameters were minimal after the total eclipse in the period from 15:30 to 16:15. The abrupt decrease in the amplitude of fluctuations of the surface temperature during the solar eclipse is readily seen in Fig. 3. Calculations showed that the variance of air-temperature pulsations during the solar eclipse decreased more than ten times. The intensity of dynamic turbulence also decreased considerably: the turbulent kinetic energy E decreased by a factor of 2.5 and the variance of pulsations of the wind-velocity vertical component decreased by a factor of 2.3.

The influence of a solar eclipse on the regime of turbulence also clearly manifests itself in changes in the power-density spectra of turbulent pulsations of the wind-velocity components and air temperature [12]. As an example, Fig. 6 shows the results of calculations of the power-density spectra of air-temperature turbulent pulsations in the ASL before the solar eclipse for the period from 12:45 to 14:45 (curve *1*) and after the eclipse for the period from 16:15 to 17:45 (curve *2*).

It should be noted that the regime of air-temperature turbulent pulsations in the period from 14:03 to 14:15 hardly differed at all from the regime of preeclipse pulsations (from 12:45 to 14:15), and the regime of pulsations of the air-temperature from 16:15 to 16:29 did not differ from the corresponding regime of its posteclipse pulsations (from 16:15 to 17:45). It is easy to see that, in the entire frequency range under consideration (from 2×10^{-3} to 5 Hz), the spectral density of the power of air-temperature variations $S_T(f)$ (f is the frequency) during the preeclipse period (curve *1* in Fig. 6) is noticeably greater than that after the solar eclipse (curve *2* in Fig. 6), a result that is in compliance with the temporal variability of the variance of air-temperature pulsations.

Analysis has shown that, in a restricted frequency range, the resulting spectra $S_T(f)$ are approximated with a satisfactory accuracy by power-law spectra $S_T(f) = Af^{-k}$. In particular, in the frequency range from about 0.45 to 5 Hz, the preeclipse spectrum $S_T(f)$ (curve *1* in Fig. 6) is satisfactorily approximated by a power-law spectrum with an exponent of $k \cong 1.85$

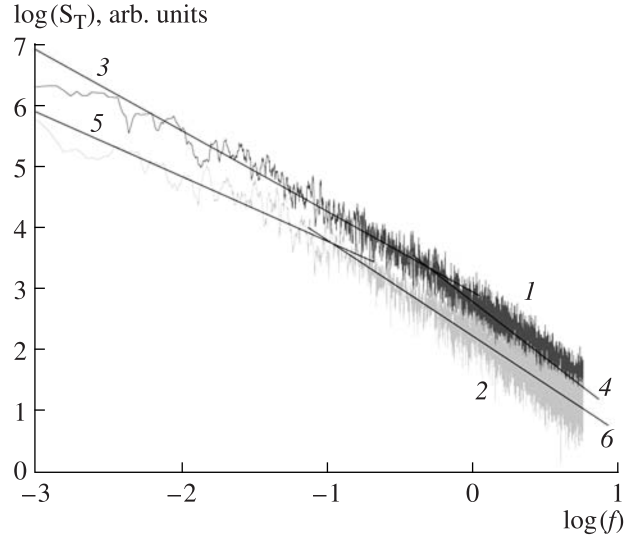

Fig. 6. Spectral density of the power of turbulent pulsations of the air temperature in the atmospheric surface layer (*1*) before and (*2*) after the eclipse. Lines *3, 4, 5*, and *6* are approximating power-law spectra.

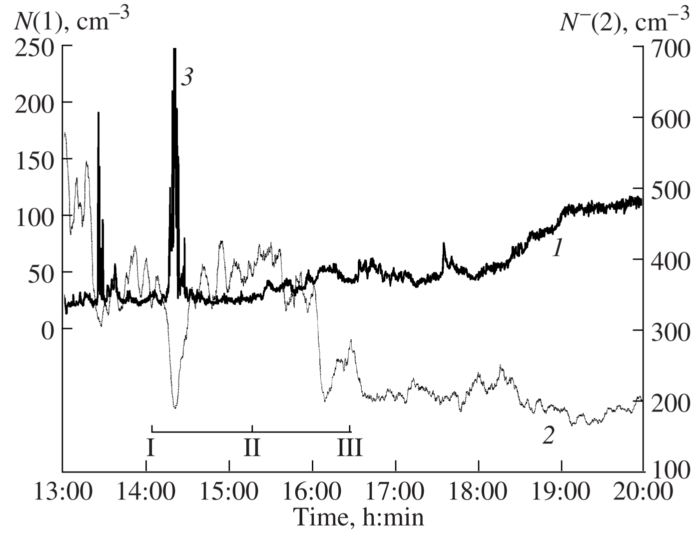

Fig. 7. (*1*) Variations in the differential number concentration of aerosol particles with sizes of 0.20–0.25 μm (15-s time averaging) and (*2*) the concentration of negative light ions (5-min time averaging) in Kislovodsk on March 29, 2006 (*3* is the outburst of aerosol concentration in smoke-loaded air; I, III, and II are the beginning, termination, and totality of the eclipse, respectively).

(curve *4* in Fig. 6) and, in the frequency range from 2×10^{-3} to 0.45 Hz, by a power spectrum with the exponent $k \cong 1.32$ (curve *3* in Fig. 6). A piecewise-power-law approximation of $S_T(f)$ is also acceptable for the posteclipse period: for the frequency range from about 0.1 to 5 Hz, $k \cong 1.57$ (curve *6* in Fig. 6) and, for the range 0.002–0.1 Hz, $k \cong 1.06$ (curve *5* in Fig. 6). Thus, the power-density spectra of air-temperature pulsations also noticeably change during the solar eclipse. Spectral analysis of wave processes is beyond the scope of this study.

Parameters of surface aerosol. As is noted above, the relative air humidity during the solar eclipse increased by 10–15% but was not greater than 55%. In this case, the sizes of watered aerosol particles could not change substantially [13]. Therefore, direct influence of the solar eclipse on the parameters of atmospheric aerosol was insignificant. The variations in atmospheric-aerosol parameters that were observed in Kislovodsk on March 29, 2006, were caused by other factors, including indirect influence of the solar eclipse caused, for example, by changes in the regime of mesoscale circulation.

Figure 7 presents the results of measurements of the differential number concentration of aerosol particles in the size range ladenAS-P laser aerosol spectrometer that were conducted in Kislovodsk on March 29, 2006, in the period from 13:00 to 20:00 (curve *1*). The outbursts of the number concentrations of aerosol particles, including the strong outburst at 14:00 (curve *3* in Fig. 7), were caused by the advection of smoke-laden 0.2–0.25 μm with on air from the areas adjacent to Kislovodsk, in which frequent steppe fires were observed on March 29, 2006, and during the preceding days. Numerous outbursts of the increased mass concentration of submicron aerosol in the short-term periods in which there was smoke over Kislovodsk or its districts were also recorded with the use of a miniature flow-type nephelometer. It should be noted that, apart from the aforementioned short-term outburst at 14:00, no considerable smoking was observed during the solar eclipse in Kislovodsk, and, consequently, there was no noticeable action of smoke aerosol on the radiation regime of the urban atmosphere. Beginning approximately at 15:30, the concentration of submicron aerosol in Kislovodsk started to increase gradually, which was apparently due to the transfer of an inhomogeneously polluted air mass.

Variations in the concentrations of atmospheric ions. During the solar eclipse, we measured concentrations of atmospheric ions in the ASL. The results of measurements of the concentrations of negative light ions with a SIGMA-1 counter are presented in Fig. 7 as an example (curve *2*). A sharp drop of the ion concentration in smoke-loaded air at 14:20 is clearly seen. This drop is apparently caused by a decrease in the lifetime of light ions at a large concentration of aerosol [9].

It is unlikely that the decrease in the concentration of light ions at about 16:00 can be explained only by an increase in the concentration of submicron aerosol. A decrease in the radon concentration in the ASL can likewise play a considerable role here. Unfortunately, the radon concentration was not measured. Apparently, no noticeable direct influence of the eclipse on the concentration of negative light ions in the ASL in Kislovodsk have been found.

CONCLUSIONS

(1) The relative decrease in the accumulated sum of shortwave solar radiation caused by the eclipse was 10–12%.

(2) The maximum decrease of the air temperature during the solar eclipse attained 3.5°C in the atmospheric surface layer and 2°C at the height 600 m. The time delay of attaining the minimum air temperature with respect to the middle of total eclipse was 20 min in the atmospheric surface layer and 40 min at heights of 200 to 600 m.

(3) A decrease in the air-cooling rate with height during the solar eclipse increased the stability of the lower 200-m layer of the atmosphere. Changes in the thermal regime of the atmospheric boundary layer caused by the eclipse are noticeably smaller than the corresponding intradiurnal variations in the vertical temperature profile.

(4) The intensity of thermal and dynamic turbulence considerably decreased during the solar eclipse. In the period of minimum temperature, the turbulent kinetic energy decreased by a factor of 2.5 compared to the mean turbulent energy in the preeclipse period; the turbulent heat flux decreased by a factor of 3.5; the variances of pulsations of the wind-velocity vertical component and the air temperature decreased by factors of 2.3 and 10, respectively.

(5) Owing to the solar eclipse, the spectral density of the power of turbulent pulsations of the air temperature noticeably decreased in the entire frequency range under consideration (2×10^{-3}–5 Hz).

(6) No direct influence of the solar eclipse on surface-aerosol parameters have been detected, a phenomenon that is explained, in particular, by comparatively low values of the relative air humidity in the atmospheric surface layer.

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