Diurnal dynamics of the optical radiation extinction by aerosol as studied in hazes along the near-ground and slant paths

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Received December 29, 2002

The diurnal dynamics of the total extinction of optical radiation by aerosol in the near-ground layer $\alpha(\lambda)$ and in the atmospheric column $\tau^A(\lambda)$ in the summer period is studied. It is shown that the dynamics of these characteristics, as well as that of the fine components, is significantly different, which is one of the factors breaking their mutual correlation. It was found experimentally that the peak of aerosol optical depth near $\lambda = 1.06$ μm was observed at 10–11 a.m., rather than at 4–5 p.m. as assumed before. This indicated indirectly that after 11 a.m. the coarse aerosol began to deposit to the lower atmospheric layers. The daily transformation of the average spectral dependence of the effective aerosol height of the atmosphere $H_0(\lambda)$ was analyzed in the region of 0.44–1.06 μm and a peak in the $H_0(\lambda)$ spectrum was revealed near $\lambda = 0.52$–0.56 μm. This peak was observed only when the fine component of the aerosol depth was minimum. It was assumed that this peak was caused by the medium-disperse particles of possibly stratospheric origin.

Statement of the problem

Statistical characteristics of the spectral aerosol extinction coefficients $\alpha(\lambda)$ and aerosol optical thickness $\tau^A(\lambda)$ obtained from simultaneous measurements of the atmospheric transmittance in the wavelength range 0.44 to 1.06 μm were considered in our paper[1] devoted to the study of joint variability of the optical radiation extinction by aerosol along the near-ground and slant paths (let us note that the sign ε_λ^A was used for notation of the aerosol extinction coefficient $\alpha(\lambda)$ in Ref. 1).

Correlation analysis of these data has shown that, in the general case, correlation between the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$ is quite weak. The correlation coefficient took its maximum $\rho_{\alpha,\tau} = 0.36$ (the level of significance is 0.16) in the visible range. Under some conditions, the correlation coefficients between these parameters can reach 0.8 (see, for example, Ref. 2). It enables us to conclude that in our case correlation between the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$ is destroyed by some factors.

Different contribution of coarse aerosol fraction to variations of $\alpha(\lambda)$ and $\tau^A(\lambda)$ can be considered as one of such factors. To check this assumption, the estimating division of the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$ into components caused by scattering of radiation by particles of coarse (with the radius of $r > 1$ μm) and submicron ($0.1 \le r \le 1$ μm) fractions was performed[1] and the correlation coefficients between submicron components were calculated. It occurred that exclusion of the coarse component from $\alpha(\lambda)$ and $\tau^A(\lambda)$ practically does not improve correlation between these parameters.

In order to continue the study of the reasons of weak correlation between extinction of optical radiation by aerosol in the near-ground layer and in the atmospheric column, we consider in this paper some peculiarities of diurnal dynamics of the submicron and coarse components of $\alpha(\lambda)$ and $\tau^A(\lambda)$ which make important contribution to the general spectrum of variability of these parameters. Besides, diurnal dynamics of the effective height of the aerosol atmosphere $H_0(\lambda) = \tau^A(\lambda)/\alpha(\lambda)$ is analyzed, which characterizes the height distribution of atmospheric aerosol. Investigations of the peculiarities of the parameter $H_0(\lambda)$ are necessary in studying the origin of intermediate dispersed aerosol fraction, which plays determining role in formation of the rarely observed effect of anomalous transparency of the atmosphere.[3]

Characteristics of the experimental data

The principal aspects of instrumentation and technique for obtaining the optical and meteorological information are described in details in Ref. 1. Let us only briefly remind here that the results of independent measurements of spectral transparency of the atmospheric column and its near-ground layer at the wavelengths of $\lambda = 0.44$, 0.48, 0.52, 0.56, 0.69, 0.87, and 1.06 μm were used for obtaining the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$. Measurements were carried out nearby Tomsk in warm seasons of 1995–2000.

Measurements of the atmospheric optical thickness $\tau(\lambda)$ were carried out by means of a sun photometer[4] in the periods when Sun was not hidden

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behind clouds. The hourly mean values $\tau(\lambda)$ were calculated from the data obtained, then the aerosol component $\tau^A(\lambda)$ was isolated by means of the LOWTRAN–5 software package.[5]

Measurements of the horizontal transmission of the atmosphere were carried out by long-path method along a 830 m long slant path using the instrumentation complex described in Ref. 6. The array of the total extinction coefficients of radiation $\varepsilon(\lambda)$ was formed from the measured values of the atmospheric transmittance, which then was used for statistical account of the contribution of molecular absorption of radiation by atmospheric gases and isolation of the coefficients $\alpha(\lambda)$ by means of the multiple linear regression.[7] Measurements of the near-ground atmospheric transmission were carried out round-the-clock with the periodicity of 1 measurement cycle every 3–4 hours.

Formation of the combined array $\{\alpha(\lambda); \tau^A(\lambda)\}$ was based on a series of hourly mean values of the optical thickness. Then the corresponding hourly mean values $\alpha(\lambda)$ were calculated for the time of $\tau^A(\lambda)$ measurement by means of interpolation within 3–4-hour time intervals. The resulting data array included 18 days of measurements where the number of measurement cycles was maximum.

All optical investigations were accompanied by measurements of absolute, a, and relative, RH, humidity and air temperature t in the near-ground layer. Besides, the column density of water vapor W was measured with a sun photometer in the spectral range $\lambda = 0.94$ μm. The table presents the number of measurement cycles in different years and corresponding values of meteorological parameters.

Year, month	Number of measurements	Measured parameter	Mean value	Rms deviation	Max	Min
1995, June–July	130	t, °C	24.02	5.07	29.8	7.3
		RH, %	66.55	10.70	99	46
		a, g/m^3	11.27	1.92	14.9	7.7
		W, g/cm^2	1.82	0.53	3.1	0.7
1999, June	52	t, °C	19.59	3.49	24.5	12.6
		RH, %	46.71	8.24	72	33
		a, g/m^3	7.86	1.14	9.6	6.2
		W, g/cm^2	1.68	0.50	2.5	0.9
2000, July	26	t, °C	19.58	4.38	25.5	14
		RH, %	50.85	9.94	65	39
		a, g/m^3	7.74	1.51	10	5.9
		W, g/cm^2	1.71	0.44	2.2	1.1
1997, September	26	t, °C	12.39	5.45	20.1	6.2
		RH, %	66.46	11.11	84	50
		a, g/m^3	7.34	1.59	9.2	5.5
		W, g/cm^2	1.26	0.17	1.5	1.0

For definiteness, the array-mean behavior of temperature and humidity (a, RH, W) of air since 6 a.m. until 6 p.m. are shown in Fig. 1. Let us note that the mean solar time for the region under consideration is presented here and below, and, to calculate the local time in Tomsk, one should add approximately 2 hours 20 minutes to the solar time. As is seen, diurnal behavior of temperature and relative humidity (curves *1* and *2*) is quite usual and no special comments are needed. Absolute humidity (curve *3*) changes insignificantly during a day, and is characterized by weakly pronounced morning and evening maxima. Column density of water vapor (curve *4*) continuously increases since morning until 4 p.m. that completely agrees with the diurnal behavior of temperature. It can be quite logically explained by convective emission of water vapor from the underlying surface as it is heated.

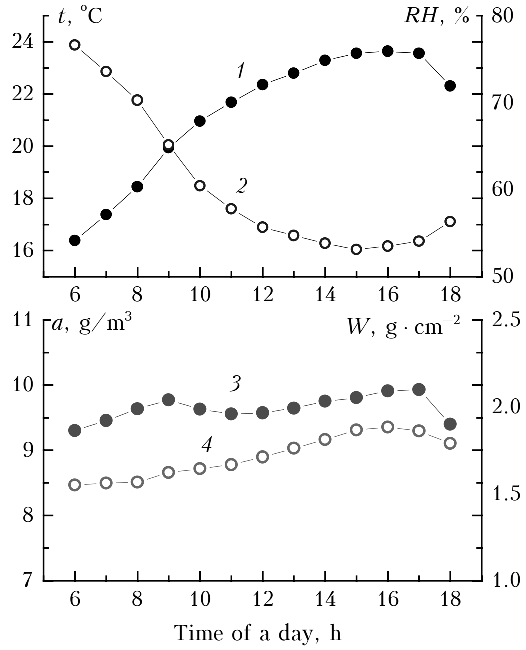

Fig. 1. Diurnal behavior of the averaged meteorological parameters of the atmosphere during optical measurements.

Analysis of the data obtained

To study the peculiarities of the diurnal dynamics of the optical radiation extinction by aerosol along the near-ground and slant paths, mean values of the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$ for each hour since 6 a.m. until 6 p.m. in the entire wavelength range were calculated using the array of hourly mean values. The calculated results are shown in Fig. 2 for two extreme wavelengths 0.44 and 1.06 μm. Diurnal behavior of the effective height of the aerosol atmosphere $H_0(0.44)$ and $H_0(1.06)$ are also presented here. Let us note that all data at intermediate wavelengths are qualitatively similar.

As is seen from Fig. 2*a*, the aerosol extinction coefficients $\alpha(0.44)$ and $\alpha(1.06)$ in the near-ground layer of the atmosphere, in the period since 9 a.m. until 6 p.m., vary practically synchronically. This is an evidence of the fact that diurnal dynamics of the parameters $\alpha(0.44)$ and $\alpha(1.06)$ in this case is, in principle, related to the change of the number density of coarse particles that make adequate contribution to the extinction of visible and IR radiation by aerosol.

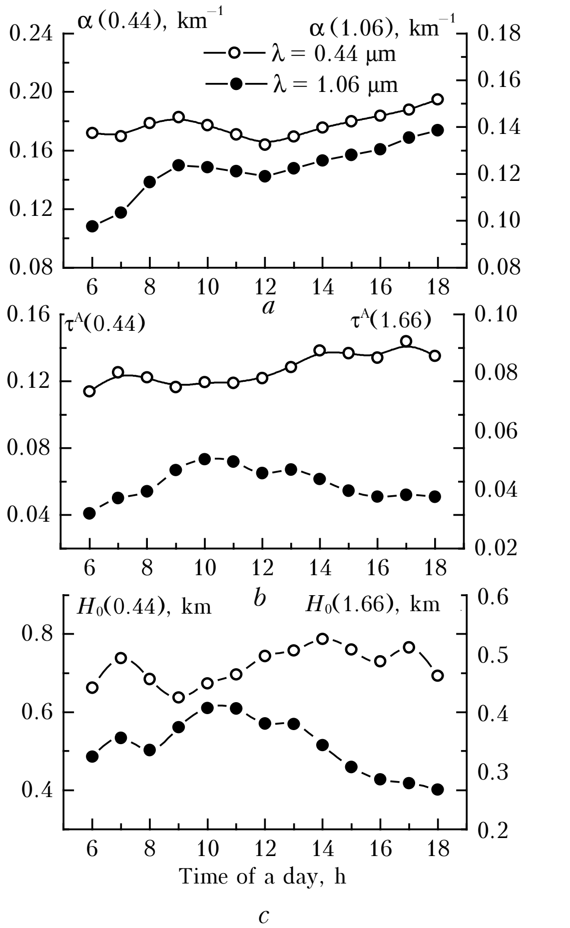

Fig. 2. Diurnal behavior of the averaged aerosol extinction coefficient $\alpha(\lambda)$, aerosol optical thickness $\tau^A(\lambda)$, and the effective height of the aerosol atmosphere $H_0(\lambda)$ at the wavelengths of 0.44 and 1.06 μm.

The increase of both parameters is observed in the period from 6 to 9 a.m., but the rates of increase are different. The coefficient $\alpha(1.06)$ increases in this period by approximately 20%, and $\alpha(0.44)$ increases only by 5%. As the coefficient $\alpha(1.06)$ under near-ground conditions is significantly determined by scattering of radiation by coarse particles, one can suppose that the revealed increase of $\alpha(1.06)$ in the period since 8:20 until 11:20 of local time is related to the morning convective emission of the particles of coarse fraction.

Lower variability of the coefficient $\alpha(0.44)$ in this time interval is caused by simultaneous effect of two contrary processes, when the increase of $\alpha(0.44)$ due to the aforementioned increase of the number density of coarse particles is compensated for by a decrease of the finely dispersed component of $\alpha(0.44)$ due to the displacement of the mean radius of submicron particles to the range of smaller size at a decrease of relative humidity of the air (see Fig. 1, curve *2*). This problem will be considered below in a more detail when analyzing the diurnal variability of the submicron component of the coefficient $\alpha(0.44)$.

Subsequent increase of the coefficients $\alpha(0.44)$ and $\alpha(1.06)$ since noon until 6 p.m. is also related to the convective emission of coarse particles from the underlying surface that is confirmed by significant correlation of the parameter $\alpha(1.06)$ with air temperature in this period (the correlation coefficient is 0.69). Estimation of the reliability carried out upon the Student t-criterion for the probability of 0.95 shows that the diurnal variations of the aerosol extinction in the visible wavelength range is not reliable for the considered data array, and is quite reliable in the IR range.

Diurnal behavior of the aerosol optical thickness of the atmosphere $\tau^A(\lambda)$ in the visible and IR regions shown in Fig. 2*b* also has some peculiarities. It is seen that, on the average, the parameter $\tau^A(\lambda)$ weakly increases during a day, while the value $\tau^A(1.06)$ noticeably increases since 6 until 10–11 a.m. and then decreases by 6 p.m. Such a diurnal behavior of the aerosol optical thickness of the atmosphere in the IR is an evidence of the fact that coarse aerosol in the afternoon begins to settle to the lower layers of the atmosphere. It is not clear yet why it occurs so early in summer at well-developed convective fluxes. Estimation of the reliability of the diurnal behavior of the aerosol thickness of the atmosphere carried out upon the Student t-criterion for the probability of 0.95 shows that it is not reliable in the visible range and is quite reliable in the IR. On the whole, analysis of Figs. 2*a* and *b* shows different manners of the diurnal dynamics of the aerosol extinction in the near-ground layer and in the atmospheric column, that, undoubtedly, is one of the important factors destroying the correlation between the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$.

The diurnal behavior of the effective height of the aerosol atmosphere $H_0(\lambda)$ shown in Fig. 2*c* shows that at 2 p.m. it takes maximum value about 800 m, in the range λ = 0.44 μm. Maximum values of $H_0(\lambda)$ in the range λ = 1.06 μm are observed between 10 and 11 a.m. and are about 430 m.

In order to study the factors leading to different diurnal dynamics of the total aerosol extinction in the near-ground layer and in the atmospheric column in a more detail, it seems to be interesting to study the diurnal dynamics of the parameters $\alpha(\lambda)$ and $\tau^A(\lambda)$ separately for fine and coarse components. One can do it if supposing that the optical properties of aerosol atmosphere in the visible range are essentially determined by two fractions of aerosol, submicron and coarse fractions, and in the range 1.06 μm it is determined only by the coarse fraction. Then, for example, the total aerosol extinction coefficient $\alpha(\lambda)$ can be presented in the form of two components:

$$\alpha(\lambda) = \alpha(\lambda)_{\rm sm} + \alpha(\lambda)_{\rm c} \approx \alpha(\lambda)_{\rm sm} + \alpha(1.06), \qquad (1)$$

where the index sm denotes the component caused by submicron particles, and c denotes the contribution of coarse fraction. For brevity, the formula for the submicron component can be written in the form

$$\alpha(\lambda)_{sm} \approx \alpha(\lambda) - \alpha(1.06) \approx \Delta\alpha(\lambda).$$

The aerosol optical thickness can be presented in analogous form:

$$\tau^A(\lambda) = \tau^A(\lambda)_{sm} + \tau^A(\lambda)_c \approx \tau^A(\lambda)_{sm} + \tau^A(1.06) \quad (2)$$

and its submicron component is:

$$\tau^A(\lambda)_{sm} \approx \tau^A(\lambda) - \tau^A(1.06) \approx \Delta\tau^A(\lambda).$$

Such a division was done for each ith spectrum and then mean values of submicron and coarse components of $\alpha(\lambda)$ and $\tau^A(\lambda)$ were calculated for every hour.

Diurnal variability of the values $\Delta\alpha(0.44)$ and $\Delta\tau^A(0.44)$ is shown in Fig. 3*a*.

It is seen that the value $\alpha(0.44)$ noticeably decreases in the period from 6 a.m. until noon that is in complete agreement with the behavior of relative humidity of air (see Fig. 1) and then since noon until 6 p.m. it increases a little bit. At the same time, temporal behavior of the component $\Delta\tau^A(0.44)$ is characterized by two maxima at 7 a.m. and 5 p.m. and wide minimum at 9–11 a.m. The difference in the dynamics of the parameters $\Delta\alpha(0.44)$ and $\Delta\tau^A(0.44)$ in the first half of the day is, obviously, related to the process of drying (by the terminology of G.V. Rosenberg[8]) of small particles at a decrease of relative humidity of air, which is more effective in the near-ground layer. Let us note that, according to Ref. 8, when drying, the maximum of the particle size-distribution function shifts to the range of smaller size at the same number density of particles.

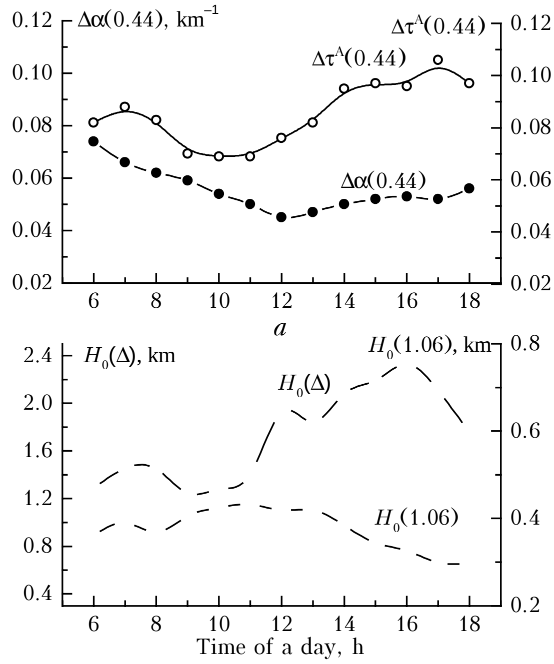

Fig. 3. Diurnal behavior of the averaged values of fine components of the aerosol extinction coefficient $\Delta\alpha(0.44)$, aerosol optical thickness $\Delta\tau^A(0.44)$, and the effective height of the aerosol atmosphere $H_0(\Delta)$.

The differences in the diurnal behavior of $\Delta\alpha(0.44)$ and $\Delta\tau^A(0.44)$ in the second half of the day are, possibly, caused by the peculiarities of the convective emission of fine particles from the underlying surface to the near-ground layer and from the near-ground to higher layers of the atmosphere. However, one should note that, according to the Student t-criterion, only the variability of the parameter $\Delta\alpha(0.44)$ in the period from 6 a.m. until noon is significant with the probability of 0.95. So the physical hypotheses about the diurnal dynamics of the $\Delta\alpha(0.44)$ in the period from noon until 6 p.m. and $\Delta\tau^A(0.44)$ during whole day should be considered only as tentative.

Diurnal behavior of the submicron component of the effective height of the atmosphere $H_0(\Delta) = \Delta\tau^A(0.44)/\Delta\alpha(0.44)$ that characterizes the height of spread of finely dispersed aerosol is shown in Fig. 3*b*. It is seen that in the case when the height of homogeneous atmosphere has been caused by only fine particles, its maximum value in summer in Western Siberia is observed at 4 p.m. and is about ~ 2300 m.

As was mentioned above, one of the problems stated in this paper is the study of diurnal variability of the effective height of the aerosol atmosphere $H_0(\lambda)$. These investigations are necessary for the study of origin and sources of intermediate disperse aerosol fraction that play important role in the effect of anomalous transmission of the atmosphere. The study of the nature of these particles and their sources will allow to make a certain statement on the physical mechanisms of formation of the anomalous spectral dependence of the aerosol optical thickness.

A hypothesis is considered in Ref. 9, according to which the intermediate disperse aerosol is formed at settling of the coarse volcanic aerosol from the stratosphere, so it has a large height of spread. This means that if very clear air mass with low content of particles of the accumulative fraction has invaded the region, then, indeed, stratospheric intermediate disperse aerosol determines the spectral structure of aerosol extinction in the atmospheric column. However, in the general case, when saying about the sources of intermediate disperse fraction of aerosol, except stratosphere, one should consider also the underlying surface as a powerful and continuously operating source of coarse and intermediate disperse fraction of aerosol.

Let us note that several days are necessary for formation of accumulative fraction of aerosol in the region (after the clear air mass has come), while intermediate disperse fraction in the near-ground layer is generated, at the presence of the convective fluxes, by the underlying surface continuously. Obviously, in this case anomaly of the spectral dependence can be observed not only for $\tau^A(\lambda)$ but also for $\alpha(\lambda)$.

The hypothesis[9] was experimentally examined in the frameworks of the data array under discussion based on analysis of average spectral dependences of the aerosol extinction coefficient, aerosol optical thickness, and the height of homogeneous atmosphere in the wavelength range 0.44 to 1.06 μm obtained during a day at 6 and 11 a.m. and at 6 p.m. The spectra $\alpha(\lambda)$, $\tau^A(\lambda)$, and $H_0(\lambda)$ are shown in Fig. 4.

Analysis of the temporal transformation of the spectrum of $\alpha(\lambda)$ for the considered data array on the whole is an evidence of the increase in the number density of particles of the coarse fraction in the near-ground layer during a day (Fig. 4*b*). Temporal variability of the spectral dependence of the aerosol thickness $\tau^A(\lambda)$ in the daytime is mainly related to the changes in the number density of particles of the coarse fraction, and in the evening it is related to the number density of fine aerosol particles (Fig. 4*a*).

The peculiarities of the diurnal transformation of the averaged spectral dependence of the effective height of aerosol atmosphere $H_0(\lambda)$ are shown in Fig. 4*c*, where the maximum is well seen in the spectrum of $H_0(\lambda)$ in the region λ = 0.52 to 0.56 μm. Let us note that the maxima are observed at 6 and 11 a.m., when the fine component of the aerosol thickness is minimum.

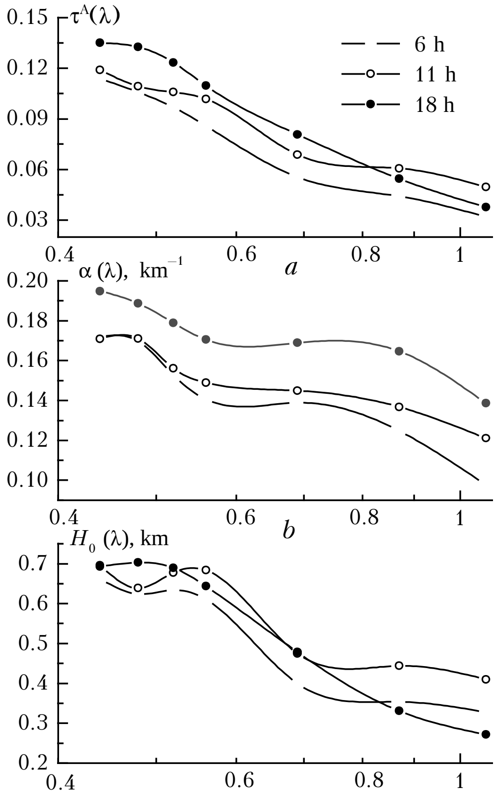

Fig. 4. Transformation of the spectral structure of averaged aerosol extinction coefficient $\alpha(\lambda)$, aerosol optical thickness $\tau^A(\lambda)$, and the effective height of the aerosol atmosphere $H_0(\lambda)$ in the wavelength range 0.44 to 1.06 μm obtained at 6 and 11 a.m. and at 6 p.m.

At 6 p.m., when the contribution of fine aerosol to $\tau^A(\lambda)$ has decreased, no maxima are observed. Physically such a maximum means that under some conditions the extinction of radiation by aerosol in this wavelength range is stronger than that in the near-ground layer. Taking into account this remark, the fact of existence of such a maximum is, possibly, an indirect confirmation of the hypothesis[9] about stratospheric origin of the intermediate disperse fraction of aerosol. Obviously, one can draw more certain conclusions about this problem from analysis of the aerosol microstructure characteristics obtained from inverting the spectra $\tau^A(\lambda)$ and $\alpha(\lambda)$.

Conclusion

The analysis of the available experimental data has shown that, in the frameworks of the considered data array, the diurnal variability of the total aerosol extinction in the near-ground layer $\alpha(\lambda)$ and in the atmospheric column $\tau^A(\lambda)$ in summer are different. The diurnal dynamics of the components of $\alpha(\lambda)$ and $\tau^A(\lambda)$ due to fine aerosol fraction is also different. This fact is one of the important factors destroying their correlation.

It is experimentally shown that the aerosol optical thickness in the range λ = 1.06 μm increases since 6 until 10–11 a.m., then decreases during a day. Such a diurnal behavior of the aerosol optical thickness of the atmosphere in the IR is an indirect evidence of the fact that coarse aerosol after 11 a.m. begins to settle to the lower layers of the atmosphere.

The maximum in the spectrum $H_0(\lambda)$ situated in the range λ = 0.52 to 0.56 μm observed only under conditions when the component of the optical thickness due to fine aerosol has been minimum is revealed from analysis of the averaged spectral dependences of the effective height of the aerosol atmosphere. Physical interpretation of this maximum does not contradict the hypothesis on the stratospheric origin of intermediate disperse fraction of aerosol which plays an important role in the formation of anomalous spectral dependence of the aerosol optical thickness.

Acknowledgments

The work was supported in part by Russian Foundation for Basic Research (Grant No. 01–05–65197).

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