DIURNAL VARIABILITY OF AEROSOL EXTINCTION IN HAZE OF ARID ZONE

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An array of the optical meteorological parameters of the atmosphere of an arid zone is used to analyze the diurnal variability of the aerosol extinction coefficient in the visible and IR spectral ranges for three seasons (spring, summer, and fall). The most pronounced variability of the aerosol extinction coefficient is found only for the visible wavelength range for spring or fall haze and for the entire wavelength range from 0.44 *to* 4 μm *for summer haze. Physical mechanisms contributing to the diurnal variability of the aerosol extinction under conditions of the arid zone are discussed.*

To understand better the key trends of the atmospheric aerosol turbidity, to justify methodological aspects of constructing atmospheric optical models of prognostic type, and to solve many other problems in atmospheric optics, it is very important to study multiscale processes influencing the variability of the aerosol extinction coefficient $\alpha(\lambda)$ in the near-ground haze in different geographical regions. For seasonal variability, this problem was solved by us in Ref. 1 for haze of arid zone based on the array of the coefficients $\alpha(\lambda)$ and the atmospheric meteorological parameters acquired between 1984 and 1988 near Lake Balkhash. The total data array in Ref. 1 comprised 589 spectra of coefficients $\alpha(\lambda)$ in the wavelength range 0.44–11.5 μm, of which 230 were collected in spring, 167 in summer, and 192 in fall. Statistical analysis of this data array has revealed pronounced seasonal transformation of the $\alpha(\lambda)$ spectra primarily associated with specific seasonal features of turbulent removal of aerosol particles of different size from the ground atmospheric layer under conditions of the arid zone.[1]

In addition to the seasonal transformation of the spectra of coefficients $\alpha(\lambda)$, of interest is also to study the diurnal variability of atmospheric optical parameters. Most promising for this purpose is the approach based on a combined analysis of synchronous measurements of the diurnal variability of spectral aerosol extinction coefficients in the visible and IR ranges and of the atmospheric meteorological parameters.

In the present paper, such an approach is taken using the above-mentioned array of coefficients $\alpha(\lambda)$ and the meteorological parameters acquired for the arid zone.[1] For this purpose, subarrays of data obtained during both day and night were composed from each seasonal data array. We then calculated the average values of the coefficients $\alpha(\lambda)$ for the entire wavelength range and the average atmospheric meteorological parameters together with their variances for each measurement period. Results of calculations of the aerosol extinction coefficients around the wavelengths λ = 0.55 and 3.97 μm are presented in Table I for three seasons, together with the relative air humidity (R), air temperature (t), and partial pressure of water vapor (e). We note that the data were averaged over 27 days for spring haze, over 17 days for summer haze, and over 19 days for fall haze.

Now we consider the diurnal behavior of the parameters $\alpha(0.55)$, $\alpha(3.97)$, R, and t by plotting them for each season. Mainly, the first three parameters will be analyzed, with diurnal behavior of air temperature given just to have an idea of the temperature regime for each season.

SPRING

Figure 1 shows the diurnal behavior of the above-mentioned parameters in spring. As is seen, in spring the diurnal behavior of the aerosol extinction coefficient in the visible wavelength range, $\alpha(0.55)$, correlates well with the relative air humidity R, with the maximum at 7:00, LT and the minimum at 15:00, LT. In general, a trend of the diurnal variability of coefficients $\alpha(3.97)$ is also similar to that of R, with more than 99% probability of difference, by the t-criterion, between their mean values in the morning and daytime.

From this it can be formally concluded that in spring in the arid zone the variability of aerosol extinction both at visible and IR wavelengths is primarily due to the diurnal behavior of the relative air humidity. However, it should be noted that, owing to cross-correlation of the meteorological parameters, the observed correlation between $\alpha(\lambda)$ and R may be indirect, through the third parameter. In particular, they may be related through the partial pressure of water vapor (e), when the water vapor content varies synchronously with concentration of small aerosol particles in the ground atmospheric layer.[2,3] Then due to the fact that R and e are cross-correlated, $\alpha(\lambda)$ will be correlated with R as well.

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TABLE I. Diurnal behavior of mean values and rms deviations of coefficients α(0.55) *and* α(3.97) *and meteorological parameters R, f, and e in the atmosphere of the arid zone for three seasons of the year.*

Local time	α(0.55), km^{-1}		α(3.97), km^{-1}		R, %		t, °C		e, mbar	
	$\bar{\alpha}$	σ_α	$\bar{\alpha}$	σ_α	$\bar{R}$	σ_R	$\bar{t}$	σ_t	$\bar{e}$	σ_e
					Spring (April)					
01:15	0.095	0.047	0.033	0.015	81.4	1.83	4.73	3.44	7.26	2.85
03:45	0.106	0.051	0.030	0.010	85.6	1.51	3.70	3.21	7.03	2.30
07:00	0.110	0.042	0.036	0.011	84.1	1.82	2.80	3.43	6.53	2.21
10:00	0.090	0.040	0.031	0.013	72.3	1.42	5.80	4.12	6.86	2.37
12:30	0.077	0.035	0.027	0.013	61.5	1.64	8.11	4.26	6.78	2.23
15:15	0.077	0.042	0.026	0.011	60.6	1.68	9.80	3.95	7.38	2.28
17:45	0.082	0.063	0.025	0.015	58.3	1.70	8.50	3.49	6.50	2.03
20:15	0.089	0.054	0.026	0.011	66.8	1.91	6.20	3.59	6.39	1.64
22:45	0.083	0.039	0.029	0.013	78.1	2.34	5.68	3.96	7.26	2.44
					Summer (July)					
01:15	0.061	0.013	0.070	0.029	47.7	1.43	25.4	3.37	15.4	4.74
03:45	0.071	0.038	0.079	0.055	55.2	1.95	23.4	3.56	16.2	4.29
07:00	0.065	0.026	0.073	0.036	56.1	1.83	23.6	3.40	16.1	3.34
10:00	0.055	0.022	0.064	0.028	49.8	1.18	25.6	3.33	16.6	4.64
12:30	0.057	0.025	0.058	0.022	47.0	1.11	25.9	3.88	16.5	5.81
15:15	0.049	0.028	0.056	0.025	38.4	0.98	28.4	3.71	15.0	4.73
17:45	0.043	0.018	0.051	0.022	36.5	0.84	29.4	4.05	15.0	4.69
20:15	0.054	0.020	0.060	0.025	37.4	1.14	29.6	3.77	15.4	5.24
22:45	0.054	0.018	0.064	0.024	44.6	0.86	26.8	3.26	15.4	4.31
					Fall (October)					
01:15	0.067	0.037	0.039	0.028	78.8	1.54	1.29	4.35	5.57	1.75
03:15	0.068	0.050	0.037	0.025	82.9	1.60	0.93	3.10	5.52	1.24
07:00	0.071	0.044	0.038	0.024	84.2	1.49	1.54	2.21	5.84	1.22
10:00	0.058	0.028	0.036	0.016	70.8	2.29	6.41	2.18	6.82	1.37
12:30	0.053	0.018	0.035	0.018	67.4	2.70	7.17	3.09	6.79	1.61
15:15	0.046	0.029	0.034	0.017	59.7	2.54	7.79	2.84	6.28	1.20
17:45	0.050	0.029	0.043	0.021	66.1	2.56	6.01	2.38	6.19	1.19
20:15	0.054	0.028	0.042	0.026	70.7	2.18	3.85	3.11	5.78	1.51
22:45	0.063	0.035	0.052	0.041	74.4	2.03	2.88	3.03	5.73	1.57

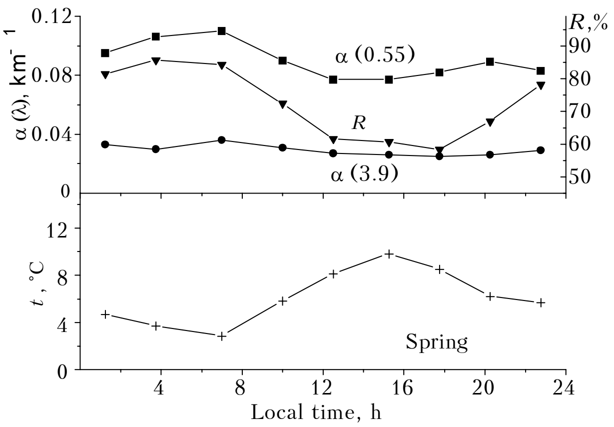

FIG. 1. Average diurnal variability of aerosol extinction coefficients α(0.55) *and* α(3.57), *relative air humidity R, and temperature t in the arid zone in spring.*

To avoid data misinterpretation in such cases, partial correlation coefficients $\rho_{\alpha(\lambda)R/e}$ should be considered, that is, correlations between α and R for fixed e. The total and partial correlations between α(λ) and R from the examined data array for two wavelengths are summarized in Table II. We note that the degree of significant correlation for this data array is about 0.15.

From the table, we see that in spring there is a significant degree of correlation between α(0.55) and R for both total and partial correlation coefficients. This in indicative of the fact that the aerosol extinction is strongly affected by the relative air humidity in this wavelength range. At the same time, the complete absence of correlation between α(3.97) and R suggests that the diurnal behavior of α(3.97) observed in Fig. 1 has nothing to do with the humidity and is likely caused by variations in the concentration of coarsely dispersed aerosols in the ground layer. Considering these two mechanisms as basic ones, it is important to elucidate their relative contribution for different wavelength ranges. To do this, let us analyze the average spectra of the coefficients $\alpha(\lambda)$ shown in Fig. 2 for the wavelength range λ = 0.44–4 μm in the daytime (curve *1*, R = 61%) and morning (curve *2*, R = 84%). Judging by the character of the spectrum transformation, the effect of the relative air humidity is most pronounced in the wavelength range between 0.44 and 1.25 μm, resulting in the change of state of submicron aerosols. Beyond this wavelength range, curves *2* and *1* are nearly parallel, probably because of the growth of coarsely dispersed aerosol particles, due to the increased relative air humidity or the increase of the concentration of coarsely dispersed aerosols in the morning hours.

TABLE II. Total and partial coefficients of correlation between $\alpha(\lambda)$ and R in the arid zone.

Season	λ = 0.55 μm		λ = 3.97 μm	
	$\rho_{\alpha_\lambda R}$	$\rho_{\alpha_\lambda R/e}$	$\rho_{\alpha_\lambda R}$	$\rho_{\alpha_\lambda R/e}$
Spring	0.38	0.56	−0.08	−0.03
Summer	0.19	−0.02	0.23	0.16
Fall	0.46	0.37	0.21	0.05

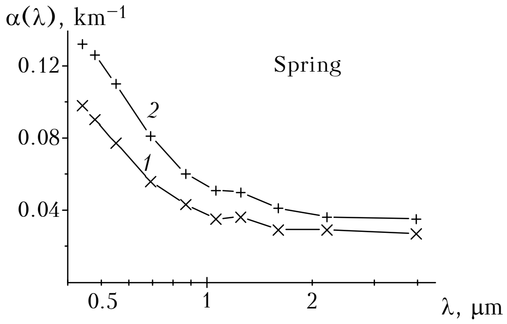

FIG. 2. Curves of the average spectral dependence of the coefficients $\alpha(\lambda)$ for spring haze in the daytime (1) and morning (2).

SUMMER

In summer (Fig. 3), the character of the diurnal behavior of the optical meteorological parameters is somewhat different. The diurnal behavior of the three parameters, namely, $\alpha(0.55)$, $\alpha(3.97)$, and R, is clearly synchronous, with the maxima at 04:00, LT and the minima at 18:00, LT. Noteworthy, the coefficients $\alpha(3.97)$ are higher than in the visible wavelength range.

At first glance, quite reasonable explanation for the diurnal variability of the aerosol extinction coefficient in the visible and IR ranges seems to be the effect of the relative air humidity; however, small values and insignificant variations of the latter (R = 36–56%), on the one hand, and a weak correlation between α and R($\rho_{\alpha_{0.55} R/e}$ = −0.02, $\rho_{\alpha_{3.97} R/e}$ = 0.16) put in doubt this explanation.

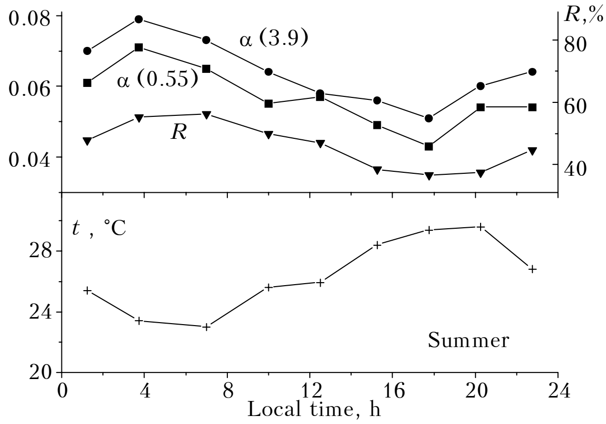

FIG. 3. The same as in Fig. 1, but for summer.

The observed synchronous diurnal behavior of R, $\alpha(0.55)$, and $\alpha(3.97)$ shown in Fig. 3 is most likely due to identical temporal behavior of two processes. Thus, the other physical mechanisms observed in the region under study should be invoked to explain the revealed relationships. To this end, let us analyze the data of Fig. 3.

Highly synchronous temporal behavior of $\alpha(0.55)$ and $\alpha(3.97)$, as well as closeness in their absolute values suggest that the major contributor to the spectral structure of aerosol extinction in summer be the coarsely dispersed aerosol. At the same time, the character of diurnal behavior of the aerosol extinction coefficient against the background of very low relative air humidity indicates that in the arid zone in summer physical mechanisms act that favor the accumulation of the coarsely dispersed aerosol in the ground air layer in the early morning and its reduction in the daytime.

This hypothesis is verified by Fig. 4 illustrating the curves of the average spectral dependence of aerosol extinction coefficients in the daytime (curve *1*) and nighttime (*2*) in summer haze. The fact that curve *2* is almost parallel to curve *1* indicates that higher values of $\alpha(\lambda)$ at night are due to higher concentration of the coarsely dispersed aerosol fraction.

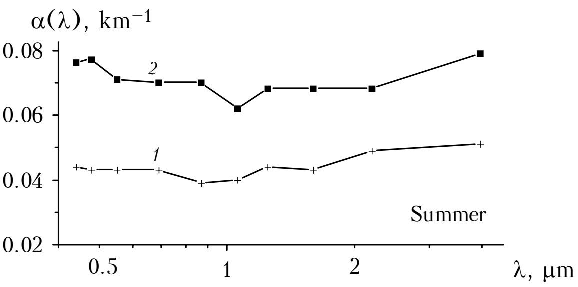

FIG. 4. Curves of the average spectral dependences of coefficients $\alpha(\lambda)$ for summer haze in the daytime (1) and nighttime (2).

It seems likely that the key mechanism responsible for the reduced concentration of the coarsely dispersed aerosol in the ground layer in the daytime is its removal to the upper atmospheric layers by convection and turbulent diffusion that, as estimated in Ref. 5, are stronger in the arid zone than in the other zones. This mechanism accounts reasonably well for the existence of the daytime minimum in curves of the diurnal behavior of α(0.55) and α(3.97), because it is this time (15:00–18:00, LT) when heating of the underlying surface is maximum and hence the removal of the aerosol from the ground layer is most intense.

An unambiguous interpretation of the morning maximum in the coarsely dispersed aerosol concentration in the ground atmospheric layer is much more difficult. One mechanism of accumulating such particles may be aerosol sedimentation from the upper aerosol layers in the absence of updrafts (after the sunset). In this case, the sedimentation rate is determined by the air drag coefficient. The air resistant force F opposing motion of a particle of radius r with velocity V is[6]

$$F = 6\pi\eta r V, \tag{1}$$

where η is the coefficient of internal friction or the viscosity of a medium [Pa·s]. Accordingly, the expression for the force of gravity has the form

$$G = mg = \frac{4}{3}\pi r^3 g(\rho - \rho_a) \tag{2}$$

where m is the mass of the particle, g is the gravitational acceleration, and ρ and ρ_a are the densities of particulate matter and air, respectively.

By equating these two forces, we find the rate of uniform sedimentation of particles under gravity, namely,

$$V = \frac{2}{9} g r^2 (\rho - \rho_a)\eta^{-1} . \tag{3}$$

Evaluation of Eq. (3) for $\rho = 1.5\ \mathrm{g{\cdot}cm^{-3}}$ and particles of radii $r = 1$, 3, 5, and 10 μm gives sedimentation rates 0.70, 6.1, 17.3, and 68 m h^{-1}, respectively.

For uniform aerosol distribution in the mixing layer (up to 1-km height) of the arid zone in the daytime in summer, different sedimentation rates may cause accumulation of coarsely dispersed particles in the ground layer on the assumption that the mechanism exists that limits the dry sedimentation of particles on the underlying surface (for example, turbulent eddies in the ground atmospheric layer). In addition, the hypothesis that coarsely dispersed aerosols are nonuniformly distributed with altitude, with the maximum concentration within the 500–600 m altitude ranges, can be advanced. Then, in the absence of updrafts, aerosols from this layer will be settled into the ground layer and the maximum concentration will be reached in the morning. Also conceivable is the aerosol accumulation in the lower atmospheric layer due to the decrease of the mixing layer height at night, etc. However, unambiguous conclusion cannot be drawn on the basis of the available experimental data.

FALL

The character of the diurnal behavior of the above-considered parameters in fall is illustrated by Fig. 5, where, as for other seasons, synchronous diurnal behavior of curves of extinction coefficient α(0.55) and relative air humidity, with the maxima at 07:00, LT and the minima at 15:00, LT is seen. Sufficiently high values and a wide range of variation of R (from 84% in the morning to 59% in the daytime), as well as a significant correlation of α(0.55) with R (see Table II), suggest that in fall, as in spring, the diurnal variability of the aerosol extinction coefficient in the visible range is primarily caused by variations of the relative air humidity. This conclusion is supported by Fig. 6 showing the spectra of coefficients α(λ) for fall haze in the daytime (curve *1*) and morning (*2*). We see that the spectrum α(λ) undergoes the most pronounced transformation between 0.44 and 1.2 μm, while its character is typical of the case in which the dominating factor of aerosol extinction variability is the relative air humidity. It also should be noted that the coefficients α(3.97) in fall haze have the nighttime peak at approximately 23:00, LT (see Fig. 5).

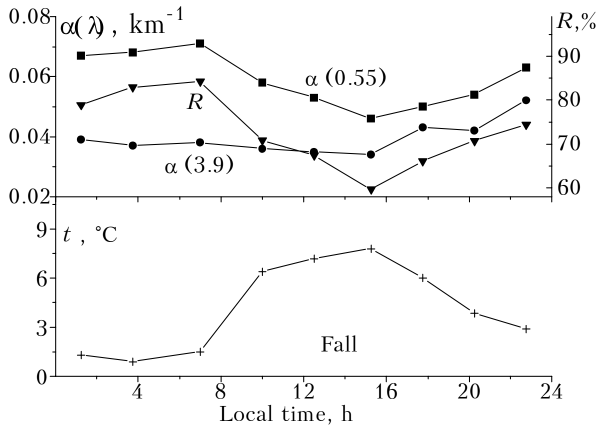

FIG. 5. The same as in Fig. 1, but for fall.

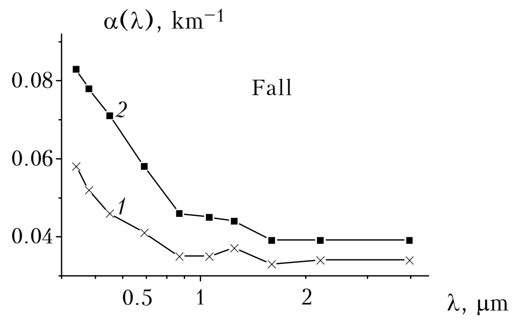

FIG. 6. Average spectra of the coefficients α(λ) for fall haze in the daytime (1) and morning (2).

Summarizing briefly our data, it should be emphasized that:

(a) in spring or fall haze of the arid zone, the diurnal variability of aerosol extinction coefficient is most pronounced in the visible spectral range with the maximum at 07:00, LT and the minimum at 15:00, LT, and is due to diurnal variability of relative air humidity. In the IR, diurnal behavior of the coefficients $\alpha(\lambda)$ is much less pronounced;

(b) in summer haze of the arid zone, the diurnal behavior of the aerosol extinction coefficient is clearly pronounced for the entire wavelength range with the maximum at 04:00, LT and the minimum at 18:00, LT, and is due to the diurnal variability of concentration of the coarsely dispersed aerosol.

On average, the aerosol extinction changes at most by a factor of 1.4 for spring–fall haze and by a factor of 1.6 for summer haze during both day and night.

REFERENCES

1. Yu.A. Pkhalagov, V.N. Uzhegov, and N.N. Shchelkanov, Atmos. Oceanic Opt. **7**, No. 10, 714–720 (1994).
2. V.N. Sidorov, Izv. Akad. Nauk SSSR, Ser. Fiz. Atmos. Okeana **18**, No. 5, 555–558 (1982).
3. M.V. Kabanov, M.V. Panchenko, Yu.A. Pkhalagov, et al., *Optical Properties of Coastal Atmospheric Haze* (Nauka, Novosibirsk, 1988), 201 pp.
4. G. Kramer, *Mathematical Methods of Statistical Analysis* [Russian translation] (Mir, Moscow, 1975), 648 pp.
5. B.D. Belan, G.O. Zadde, Yu.A. Pkhalagov, and T.M. Rasskazchikova, Izv. Akad. Nauk SSSR, Ser. Fiz. Atmos. Okeana **23**, No. 6, 622–628 (1987).
6. N.I. Koshkin and M.G. Shirkevich, *Handbook of Elementary Physics* (Nauka, Moscow, 1986), 208 pp.