ON THE POSSIBLE EFFECT OF THE AITKEN NUCLEI ON SKY BRIGHTNESS IN SUMMER

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The results of solving the radiative transfer equation by the method of spherical harmonics for the atmospheric model incorporating three aerosol fractions, namely, Aitken nuclei and the submicron and coarse fractions are analyzed. The independence of the absolute brightness phase function and the solar zenith angle, noticed by many observers at moderate and large scattering angles in the visible range results most probably from the gradual increase of the Aitken nuclei load during the morning hours and their subsequent decrease at afternoon.

The criterion for the stability of the optical properties of the atmosphere, developed by G.V. Fesenkov on the basis of the measurements of daytime transmissivity by the "long–time" Bouguer technique, is based on the theory of single scattering of light. The essence of it is that the condition of temporal constancy of the relative circumsolar aureole, calculated per unit atmospheric mass, must be satisfied.[1] In other words, the absolute brightness phase function $f(\varphi)$ must be constant at a fixed small scattering angle φ, for which the role of multiple scattering effects is assumed to be negligible.

The subsequent observations of the absolute brightness phase functions $f(\varphi)$ in the solar almukantar for various solar zenith angles Z_0 enabled E.V. Pyaskovskaya–Fesenkova to obtain the following regularity: when $f(\varphi)$ is independent of Z_0 in the region of the aureole ($\varphi \sim 2°$), the function $f(\varphi)$ would, as a rule, remain constant at every other fixed angle φ as well.[2] She did not introduce the dependence of $f(\varphi)$ on the solar zenith angle into any of the formula relating the atmospheric transmittance P to $f(\varphi)$ at large φ. There were also some suggestions to use the observations of $f(60°)$ for monitoring the stability of the atmospheric optical properties in the visible range.[2-5]

Such an independence of $f(\varphi)$ and Z_0 at large φ, where the role of multiple scattering may be significant, requires additional explaination. The first attempt of such an analysis was made in Ref. 6 and was based on calculations of the sky brightness performed in Ref. 7. It was demonstrated that in separating $f(\varphi)$ into its additive components $f_1(\varphi)$, $f_2(\varphi)$, and $f_q(\varphi)$, associated with single scattering, multiple scattering, and reflection of light from the underlying surface with the albedo q, the quantity $f_2(\varphi)$ increases with Z_0 for constant $f_1(\varphi)$, while the quantity $f_q(\varphi)$, on the contrary, decreases. Eventually a certain compensation has arisen which results in the independence of $f(\varphi)$ and Z_0 to an accuracy of several per cents. However, the accuracy of calculations of the sky brightness, attainable at that time (1958) could hardly guarantee the adequacy of such a trivial explanation of the observed phenomenon. Starting from the newly developed ideas on the optical properties of aerosol and using the modern methods for solving the radiative transfer equation in the atmosphere and for calculating $f(\varphi)$, we revise the reasons giving rise to the observed constancy of $f(\varphi)$ at various solar zenith angles. The results of this study are discussed below.

The atmospheric model, which is used to calculate the absolute brightness phase functions $f(\varphi)$ was described in Ref. 8. In particular, it was demonstrated there that the altitude weighted average of the actual aerosol scattering phase function $f_D(\varphi)$, (Ref. 9) can be represented by a sum of phase functions corresponding to three fractions of particles with lognormal size distribution including the Aitken nuclei and the submicron and the coarse aerosol fractions. The distribution parameters and the weight relations between the fractions were found. Calculations of the brightness phase function $f(\varphi)$ followed the solution of the radiative transfer equation by the method of the spherical harmonics. Note that within the applicability limits of the plane–parallel approximation ($\sec Z_0 \le 5$) the single scattering phase function is $f_1(\varphi) = f_R(\varphi) + f_D(\varphi)$ provided the optical parameters of the medium are fixed (f_R is the molecular component). This phase function is independent of Z_0, the atmospheric stratification, and the absorption effects.[10]

The brightness phase functions $f(\varphi)$ were calculated at three wavelengths (λ = 0.40, 0.55, and 0.65 μm), for three values of the turbidity factor T = 2, 3, and 4 at λ = 0.55 μm, and for three different albedo of the underlying surface q. The results of the analysis of these phase functions $f(\varphi)$ are presented below for the values calculated with the summer albedo of plant canopy, which was assumed to be Lambertian. The values of q were averaged over the experimental data.[11,12] They are given in Table I as functions of $\sec Z_0$.

TABLE I. Summer albedo of the plant canopy.

λ	Sec Z_0					
μm	1.25	2.00	2.86	3.64	4.35	5.00
0.40	0.032	0.039	0.046	0.049	0.051	0.052
0.55	0.069	0.086	0.100	0.108	0.112	0.115
0.65	0.082	0.102	0.119	0.128	0.133	0.136

Figure 1 shows the absolute single scattering $f_1(\varphi)$ and multiple scattering $f_{2,q}(\varphi)$ phase functions (the latter includes the component produced by the light reflection from the underlying surface) at λ = 0.65 μm for T = 3 and $\sec Z_0 = 5$ calculated for pure scattering. The aureole section can be distinctly seen in the plot of $f_{2,q}(\varphi)$. The

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existence of such a section in $f_{2,q}(\varphi)$ testifies to the possible effects of multiple scattering on the quantity $f(\varphi)$ at small φ if the atmospheric turbidity is strong. Table II illustrates the contribution of multiple scattering to the total sky brightness for two solar zenith angles. The data tabulated at $\varphi = 2°$ illustrate well the foregoing discussions.

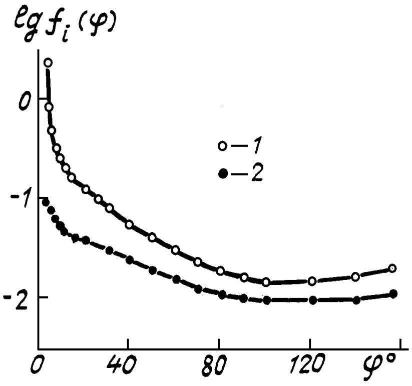

FIG. 1. Single (1) and multiple (2) scattering phase functions.

TABLE II. The contribution of $f_1(\varphi)$ to $f(\varphi)$ (in per cent).

Sec Z_0	Turbidity factor (T)								
	2			3			4		
	λ								
	0.40	0.55	0.65	0.40	0.55	0.65	0.40	0.55	0.65
	$\varphi = 2°$								
2	94	98	98	93	95	97	91	94	96
5	90	96	96	86	92	93	81	88	90
	$\varphi = 90°$								
2	42	57	61	34	46	50	28	38	41
5	33	50	54	22	35	39	15	25	28

Since the components $f_2(\varphi)$ and $f_q(\varphi)$, in contrast to $f_1(\varphi)$, depend of Z_0 one may expect $f(\varphi)$ to be dependent on Z_0 even when the optical properties of the atmosphere remains unchanged.

Table III lists the calculated ratios $r = \dfrac{f(\sec Z_0 = 5)}{f(\sec Z_0 = 2)}$. The case of pure scattering corresponds to a quantum survival probability $\omega = 1.0$. The calculated ratio r remains larger than unity for any T and λ. Since the relative error in determining $f(\varphi)$ is usually within 3–4%, when applying the short–wave aureole measurements in practice for monitoring the atmospheric optical stability, such deviations of r from unity under conditions of strong turbidity should be taken into account.

Since most of the experimental data were obtained by E.V. Pyaskovskaya–Fesenkova under conditions of weak turbidity ($T < 2$) in the wavelength range $0.48 \le \lambda \le 0.62$ μm, the choice of the optically stable days against the criterion for the coarse aerosol fraction as those with constant $f(2°)$ seems to be absolutely correct.

TABLE III. The values of r at $\varphi = 2°$ and $90°$.

φ°	Turbidity factor (T)								
	2			3			4		
	λ								
	0.40	0.55	0.65	0.40	0.55	0.65	0.40	0.55	0.65
	$\omega = 1.0$								
2	1.05	1.02	1.02	1.08	1.04	1.03	1.12	1.07	1.06
90	1.29	1.14	1.12	1.55	1.30	1.27	1.88	1.50	1.45
	$\omega = 0.9$								
2	1.04	1.02	1.01	–	–	–	1.10	–	1.04
90	1.31	1.12	1.10	–	–	–	1.82	–	1.39

When φ increases the contribution of $f_1(\varphi)$ to $f(\varphi)$ decreases, which naturally affects the dependence of $f(\varphi)$ on sec Z_0. This can be seen from Tables II and III in which the corresponding calculated results are given at $\varphi = 90°$. Although f_2 and f_q demonstrate reverse dependence on Z_0, after summation they do not compensate each other and a regular increase in $f(90°)$ with sec Z_0 exceeds the typical experimental errors. In the range $2 \le \sec Z_0 \le 5$ the logarithm of such variation may be approximated by a linear dependence. The logarithmic gradients $k(90°) = \dfrac{\Delta \lg f(90°)}{\Delta \sec Z_0}$ are plotted in Fig. 2 as functions of the optical thickness of scattering τ_1. The straight lines are clearly distinguished according to the wavelengths, and the lowest points correspond to the molecular atmosphere,[13] i.e., $T = 1$. It can be seen that the rate of increase of $f(90°)$ for larger sec Z_0 depends on the dominating contribution to τ_1: whether it is due to strong atmospheric turbidity or to large molecular optical thickness τ_R when λ decreases. Therefore, we should consider as hardly feasible the attempts to apply tabulated brightnesses, calculated for the symmetrical scattering phase functions given in Ref. 13, to account for multiple scattering of light in interpreting the experimental data obtained for strong atmospheric turbidities.

So, starting from the theoretical results an increase in $f(90\ )$ with Z_0 must occur in the case of pure scattering even in the visible range for $T \sim 2$–3. This, however, contradicts the available data of various authors[2–5]: they found $f(\varphi)$ to be independent of Z_0 at large φ for constant $f(2°)$. What then may be the reason of such a discrepancy between the theory and observations?

Let us first estimate the effect of light absorption on the daily behavior of $f(\varphi)$. In doing so, we introduce the quantum survival probability ω into our calculations of $f(\varphi)$ with the rest of the parameters remaining unchanged. The so–called background aerosols have $\omega \sim 0.9$.[14] The values of r calculated with an account of absorption are given in Table III. It follows from this table that the absorption give rise to the decrease of r in the red and green regions of the spectrum by 2–3%. Introducing $\omega = 0.65$ for $T = 2$ results in the value of $r(90°)$ to be equal to 1.10 ($\lambda = 0.55$ μm) and 1.07 ($\lambda = 0.65$ μm). In other words, the aerosol absorption of light may only partially be responsible for the observed constancy of $f(\varphi)$.

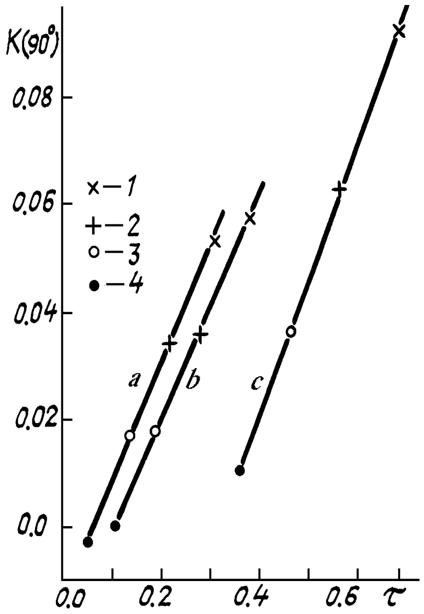

FIG. 2. The logarithmic gradient k(90°) vs the scattering optical thickness (1–4) for the subsequent values of the atmospheric turbidity factor varying from 4 *to* 1 *at* $\lambda = 0.65$ μm *(a),* $\lambda = 0.55$ μm *(b), and* $\lambda = 0.40$ μm *(c).*

A more detailed analysis of the calculated and observed data on $f(\varphi)$ must be performed in the short–wave spectral range ($\lambda \le 0.40$ μm). Here the problem of the $f(\varphi)$ dependence on Z_0, as a matter of fact, has not been studied yet, although the very fact of $f(\varphi)$ increasing with Z_0 at large φ was detected a long time ago.[6] Figure 3 presents the calculated logarithmic gradient $k(90°)$ as a function of the total optical thickness $\tau = \tau_R + \tau_D + \tau_a$ (here τ_a is the aerosol absorption optical thickness) at $\lambda = 0.40$ μm. The chosen $\tau_R = 0.36$ corresponds to the value observed at the sea level. The account of absorption does not change the behavior of $k(90°)$ vs τ for $\tau \le 0.7$, and makes it possible to draw the corresponding envelope curve through the corresponding points. The same figure shows the values of $k(90°)$ in the wavelength range 0.38–0.39 μm obtained from the spectropolarimetric observations[15] and from the measurements by a photometer with narrow–band light filter, virtually unaffected by the Forbes effect.[16] The values of $f(90°)$ were measured in summer and fall in the foothills of Zailiiskii Alatau, at an altitude of 1400 m above the sea level. The atmospheric Rayleigh optical thickness at this altitude is equal to about 0.36. The analysis incorporates the days of stable aureole data. Naturally, the errors in estimating $k(90°)$ depend on the accuracy of measurement of $f(90°)$, on the total number of experimental points, and on the magnitude of $\Delta\sec Z_0$. The maximum absolute error corresponding to the confidence level of 0.95, is shown in Fig. 3 for the case of $k(90°)$ retrieved from two points when $\Delta\sec Z_0 = 0.8$. In most cases it should be decreased by more than a factor of 2. It can be seen from this figure that on the average the experimental values of $k(90°)$ lie below the corresponding curve and hence they are less than the calculated values.

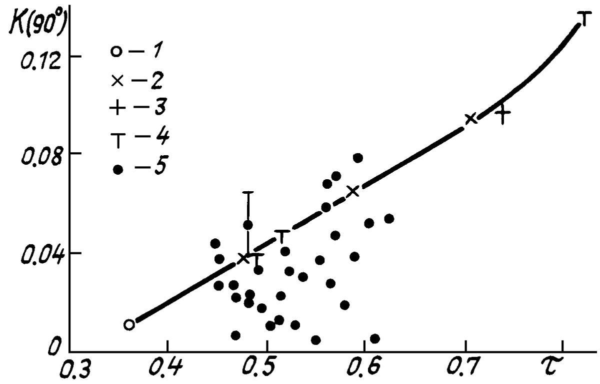

FIG. 3. The comparison of the quantity k(90°) calculated for the molecular (1) and aerosol atmospheric models for $\omega = 1.0$ *(2),* 0.9 *(3), and* 0.65 *(4) with the results of observations (5).*

The discrepancy between the theory and observations is eliminated if we assume that in summer the number of small particles in the atmosphere gradually increases from morning to noon. It should be noted that the practical data sets of various authors,[2–5] as well as our own data shown in Fig. 3, were obtained before noon. As turbidity became gradually stronger with decrease of Z_0, the logarithm of the direct solar radiation intensity lg F often remains linearly dependent of the atmospheric mass, although the Bouguer curve changes its slope.[2] The latter effect results in retrieving an erroneous (overestimated) value of the atmospheric transmittance.

We have mathematically simulated such an atmospheric optical instability. With Z_0 gradually decreasing (starting from $\sec Z = 5$) the number of the aerosol particles in each fraction was sequentially changed, so as to obtain a total increase of the aerosol optical thickness τ_D by 20% for $\sec Z_0 = 2$. However, the dependence of lg F on $\sec Z_0$ was kept linear.

The analysis of the results of calculation of $f(\varphi)$ (pure scattering) demonstrated the following.

Increasing the number of coarse particles with the parameters $\sigma^2 = 0.5$: $a = 0.8$, and $n = 1.5$ leads to a significant increase of the quantity $f(2°)$, by more than a factor of 2. Here σ^2 is the variance of the logarithmic radii, $a = \ln \rho_0$, $\rho_0 = 2\pi\rho_0/\lambda$, r_0 is the mean geometric radius of the particles; and, $n = 1.5$ is their refractive index.[17] If $\varphi > 30°$ the values of $f(\varphi)$ remain practically the same as in a stable day, i.e., $f(\varphi)$ increases with Z_0 at the fixed angle φ. Observers often note a significant increase in $f(2°)$ from morning to noon.

Increasing the number of submicron particles with $\sigma^2 = 0.4$ and $a = 0.4$ results in a practical independence of $f(\varphi)$ and Z_0 when $\varphi \le 3°$ and $\varphi \ge 40°$. However, when $\varphi = 10$–$15°$ an increase of $f(\varphi)$ by about 20% was found. As we know such an effect was never been observed in practice. Finally, an increase of the number of the Aitken nuclei with $\sigma^2 = 0.3$ and $a = -1.0$ results in an independence of $f(\varphi)$ and Z_0 at any values of φ, at least for two values of the turbidity factor (2 and 3) at two wavelengths (0.55 and 0.65 μm). Figure 4 gives an example of the calculated brightness phase functions at $\lambda = 0.55$ μm for $T = 3$ in the interval $30° \le \varphi \ge 120°$. According to the model used such phase functions correspond to an optically stable day for sec Z_0 being equal to 5 and 2. The difference between the two phase functions around $\varphi \sim 90°$ is approximately 25%. The increase of the aerosol optical thickness by 20% due to a larger load of the Aitken nuclei leads the phase function for sec $Z_0 = 2$ to the agreement within the accuracy of 2% with $f(\varphi)$ for sec $Z_0 = 5$, and this result holds for all the angles of scattering, even in the region of the aureole which is not shown in the plot.

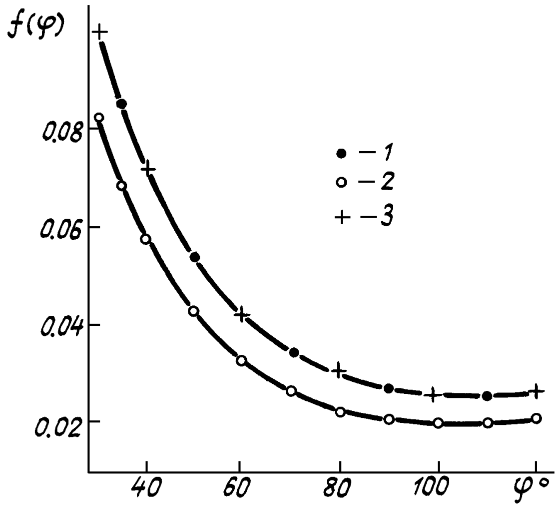

FIG. 4. The brightness phase functions for sec $Z_0 = 5$ (1) and 2 (2) in the stable atmosphere and with an account of a 20% increase in τ due to the Aitken nuclei for sec $Z_0 = 2$ (3).

A gradual loading of the atmosphere with small particles, similar in their properties to the Aitken nuclei, from morning to noon seems to be quite a feasible process. The so–called "organic evaporation" of vegetation is responsible for this.[15] Stronger fluxes of short–wave solar radiation for smaller solar zenith angles stimulate the photochemical reactions of forming of the Aitken nuclei from the gas phase. The increased number of such particles can be seen as weak blue hazes over the plant canopies. Such an instability in the aerosol particle composition of the atmosphere is manifested in the gradual increase of the optical thickness $\Delta\tau_D$ by approximately 0.01–0.03 in the visible range.

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