ON STUDYING VERTICAL PROFILES OF THE AEROSOL OPTICAL DENSITY BY HELICOPTER UV PHOTOMETERS

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A design of a helicopter UV sun photometer and mathematical techniques for processing its data are described. Vertical profiles of tropospheric aerosol optical density, obtained during summer seasons of 1985 and 1987 in the Kzyl-Orda area, are demonstrated.

Vertical profiles of aerosol radiation extinction have been studied in detail in the visible and IR spectral ranges, and respective atmospheric models are available from publications. [7] However, there are considerably fewer publications on the optical properties of atmospheric aerosols In the UV spectral range. This paper describes an ultraviolet (UV) helicopter photometer, the technique for mathematical processing of its measurement results is substantiated, and experimental data are presented on vertical profiles of the optical density of tropospheric aerosols from summertime observations of 1985 and 1987 in the vicinity of the town of Kzyl-Orda.

The on-board selective UV photometer "Minsk-I" is designed to measure total, direct, and diffuse UV solar radiation in the lower atmospheric layers. The operating principle is based on the successive measurement and comparison of the scattered and total solar radiation fluxes, arriving from the hemisphere, using the helicopter blades for a chopper. Radiation is incident upon a photodetecting system through a diffusely scattering Teflon collector, with direct radiation being modulated by the helicopter blades. When measuring the fluxes, values corresponding to the blades shading and exposing the diffuser plate are synchronously selected from the photodetector output signal. Thus, both scattered and total solar fluxes are measured. Results are recorded by either a strip chart recorder or a loop oscillograph. The direct solar radiation is obtained as the difference between the two measured values.

The instrument spectral range depends on the spectral sensitivity curve of the photomultiplier employed (FEU-124) and on the light filter used to select the measured band out of the overall spectrum. We used two filter sets, providing a transmission band with a half-width of about 20 nm and having two maxima (295 and 322 nm).

In making the measurements the KA-26 or MI-8 helicopter carrying the photometers climbed to an altitude 3–4 km and then descended to 300–100 m at an approximately constant rate. During the descent the global and diffuse solar radiation, altitude, and air temperature were recorded. The descent time amounted to 20–25 min, so that at small solar zenith distances the relative atmospheric mass could be considered constant within an accuracy of approximately 2%. The more significant error sources include the following:

1. Plane-parallel displacement of the solar beam path during helicopter descent when a cellular horizontal structure of the aerosol layers[1] is hypothesized, this can result in strong variations in the solar radiation. To check the validity of this hypothesis, additional systematic studies are needed.

2. Random variations of helicopter spatial orientation; since the photometer sensitivity depends on the angle of radiation incidence, this might also result in variations of the recorded signal. Let us assume that the angular characteristic of a photometer with flat scatterer plate is cosine, the Sun zenith angle is approximately 45° during the measurements, and the "wobble" amplitude of the helicopter axis around its mean position during descent is 5°. Then the relative error in determining the direct solar radiation will be

$$\varepsilon = \delta I/I = \mathrm{tg}\varphi\ \delta\varphi \approx 0.09$$

This is the error amplitude and its rms value will be given by averaging the squared temporal trend of that error. Let us assume the amplitude of the helicopter "swings" obeys a cosine law. Then $\sigma = \sqrt{\overline{\varepsilon^2}} \approx 7\%$, which agrees rather well with the experimental data. A simple means to exclude the errors produced by helicopter orientation instability would be to employ scattering heads with angular characteristics depending only slightly on the single of radiation incidence. Such heads of unique design are now being developed.

3. The helicopter "wobble" frequency cannot be too high; however, a high-frequency oscillation component is found in the measured signal (see Fig. 1a). Therefore, other error sources must be assumed to produce contributions comparable to that estimated above. Among these are the intrinsic noises of the pho-

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tometer and the loop oscillograph used to record the photometer output signal. Measurement accuracy can be increased significantly by using a magnetic recording system, which would introduce considerably smaller distortions into the recorded signal.

These refinements have been implemented in the updated two-channel "Minsk-IM" UV photometer.

The vertical profile of the atmospheric optical density is obtained by differentiating the log of the altitude dependence of the direct solar radiation:

$$\rho_\lambda(h) = \frac{\partial}{\partial h}\left\{\frac{\ln I_\lambda(h)}{\cos Z}\right\}, \quad H_1 \le h \le H_2, \tag{1}$$

where $\rho_\lambda(h)$ is the value of the atmospheric optical density at altitude h for wavelength λ; Z is the solar zenith angle; $I_\lambda(h)$ is the altitude dependence of the global and diffuse radiation difference signals at the same wavelength.

To differentiate experimental data containing certain errors is an incorrect operation, and to solve such a mathematical problem successfully, additional information on the behavior of the profile must be resorted to. In particular, considerations of the non-negative character of such a vertical profile of optical density together with data on the typical scale of its spatial elements can be employed. These same data can serve to choose an adequate vertical measurement step. The suggested approach is similar to the one described in Refs. 2 and 3 (as applied to the problem of data reduction to an ideal instrument, and to data smoothing); essentially, it is based on an a priori description of the desired solution. As demonstrated in Refs. 2, 3, and 4, higher solution stability with respect to measurement errors is thus achieved, as compared to that provided by the general regularization technique.[5]

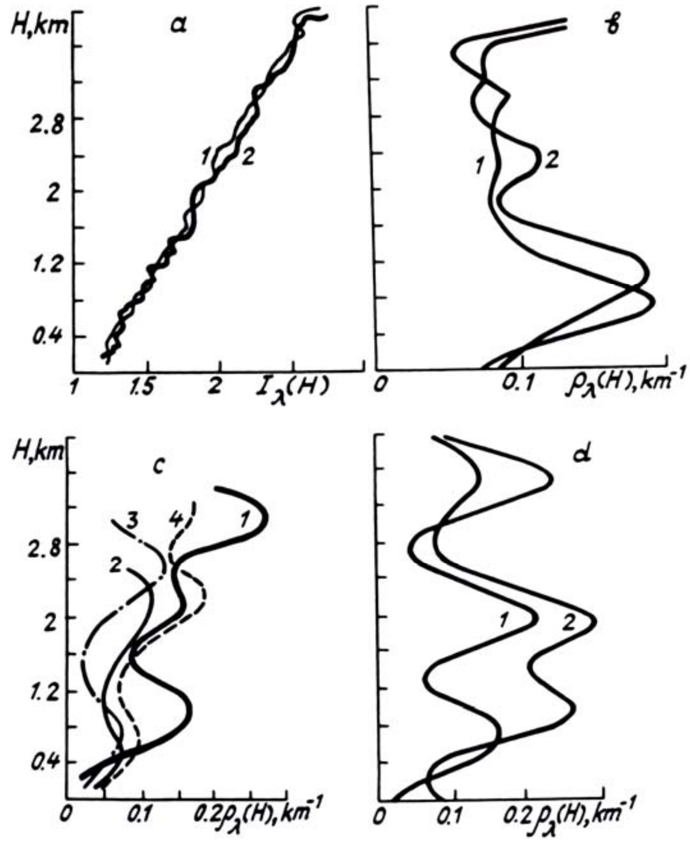

FIG. 1. Solar UV flux vs. height (a) and the obtained vertical profiles of the aerosol optical density (b, c, and d). Data taken from: a, b) July 7, 1987. Clear, cloudless, thick haze, λ = 322 nm. 12:20 LT (1), 13:00 LT (2). c) July 9, 1987. Cloudless, haze. 12:30 LT, λ = 295 nm (1), λ = 322 nm (2). 13:00 LT, λ = 295 nm (3), λ = 326 nm. (4); d) July 18, 1987. Thick haze, few cirrus clouds, λ = 295 nm. 15:20 LT (1), 17:20 LT (2).

According to Refs. 2 and 3, to take account of the non-negative character of the solution and the finite width of its fine elements the solution $\rho_\lambda(h)$ should be represented as

$$\rho_\lambda(h) = \int A(h-x)\varphi(x)dx, \quad A(x) \ge 0, \quad \varphi(x) \ge 0, \tag{2}$$

Here $A(x)$ characterizes the shape of the "elementary components", from which the distribution being sought is constructed by convoluting them with a non-negative function $\varphi(x)$. Thus, the vertical optical density profile is represented as a superposition of overlapping "elementary components". Their position on the height scale and their non-negative amplitudes (i.e., the function $\varphi(x)$) have to be determined. It is clear that the half-width of the finest detail in $\rho_\lambda(h)$ cannot be less than the half-width of a separate component $A(x)$: it should not exceed the half-width of details in the fine structure of the vertical profile, so as to yield an adequately accurate representation (2). At the same time this half-width of $A(x)$ should not be too narrow, as compared to profile details and to the digitization interval for the obtained solution of $\varphi(x)$ to remain unique and stable. The shape of the contour $A(x)$ used only affects the computational results slightly, as demonstrated by experiments.[2,3] The integration limits in Eq. (2) can be wider them the studied layer to provide adequate behavior freedom for $\rho_\lambda(h)$ at the ends of the interval.

Making use of the representation (2), the task of finding $\rho_\lambda(h)$ is reduced to the approximate solution of the integral equation

$$\int A(h-x)\varphi(x)dx \approx f(h) = \frac{\partial}{\partial h}\left\{\frac{\ln I_\lambda(h)}{\cos Z}\right\} \tag{3}$$

with respect to $\varphi(x) \geq 0$. Converting to the discrete approximation of Eq. (3)

$$\sum_j A_{ij}\varphi_j \approx f_i, \quad \varphi_i \geq 0,$$

or

$$A\vec{\varphi} \approx \vec{f}, \quad \vec{\varphi} \geq 0,$$

we find the vector $\vec{\varphi}$ from the condition of minimizing the rms error

$$|A\vec{\varphi} - \vec{f}|^2 = \min, \quad \vec{\varphi} \geq 0.$$

Then the estimate for $\vec{\rho}_\lambda$ is obtained as

$$\vec{\rho}_\lambda = A\vec{\varphi}$$

When processing the experimental data from 1987, the shape of the function $A(x)$ was chosen to be Gaussian, and its half-width was taken equal to 400 m. In other words, we assumed its possibility of a vertically stratified aerosol having a half-width of at least 400 m. This assumption agrees quite well with the results of visual observations and with data from other studies. Efficiency and stability of the computational scheme were also favorably affected by subtracting molecular scattering

$$\tau_{mol}(h) = \mu\beta(\lambda)p(h)$$

from the measured vertical profile of the atmospheric optical depth. Here μ is the relative air mass; $\beta(\lambda)$ is the molecular scattering coefficient at wavelength λ; $p(h)$ is the dependence of air pressure on height. Such a procedure was not applied to the results from 1985, and the function used for the "elementary component" was triangular. That is why profiles from that year (see below) characterize the optical atmospheric density as a whole, instead of its aerosol component alone, and differ somewhat from curves of 1987 both in shape and amplitude.

Certain results from its data processing are presented in Figs. 1 and 2. The description of measurement conditions and information on the cloudiness situation are given in figure legends.

An analysis of the results shows that the data from the newly designed UV helicopter instrumentation make possible a correct description of the visually observed stratification of the atmospheric surface layer aerosols. The largest discrepancies between the 295 and 322 nm measurement results occurred to July 27, 1987, when meteorological conditions were unfavorable. A low signal combined with relatively high measurement errors produced a low reconstruction accuracy of the vertical profile (in particular, note a total lack of radiation extinction in the 0–600 m layer (322 nm), contrasting with significant optical densities at 295 nm at the same altitudes). However, the absence of stratified aerosol on that particular day completely agrees with visual observations.

Figure 2d presents the total atmospheric optical density profile, including both aerosol extinction and molecular scattering (see above). Since the effectiveness of the latter diminishes with altitude, subtraction of the molecular scattering contribution from these curves produces a stratified vertical distribution of aerosol optical density, with the intensity at its maxima gradually increasing with height. Low values of total density at the distribution minima (Fig. 4d) result from the poorer stability of the computational scheme in cases when the total optical depth profile is differentiated and not just its aerosol part.

It follows from these results that the vertical aerosol stratification in the measurement zone was quite stable. Aerosol layers stratified at 0.8–1.2, 1.8–2.5, and 3–3.5 km; this feature was quite typical for summertime conditions in this region and was repeated annually. However, sharp anomalies were also encountered, such as the stratification diffusing or vanishing (as on July 27, 1987).

Day-to-day variations in the quantitative aerosol profiles and their diurnal trends resulting from changes in the Sun elevation cannot be monitored as yet with this instrument because of significant errors in the reconstructed vertical profiles of the aerosol optical density. The latter results from low accuracy of the initial measurements. The same obstacle hampers obtaining quantitative data on the aerosol extinction selectivity in the UV.

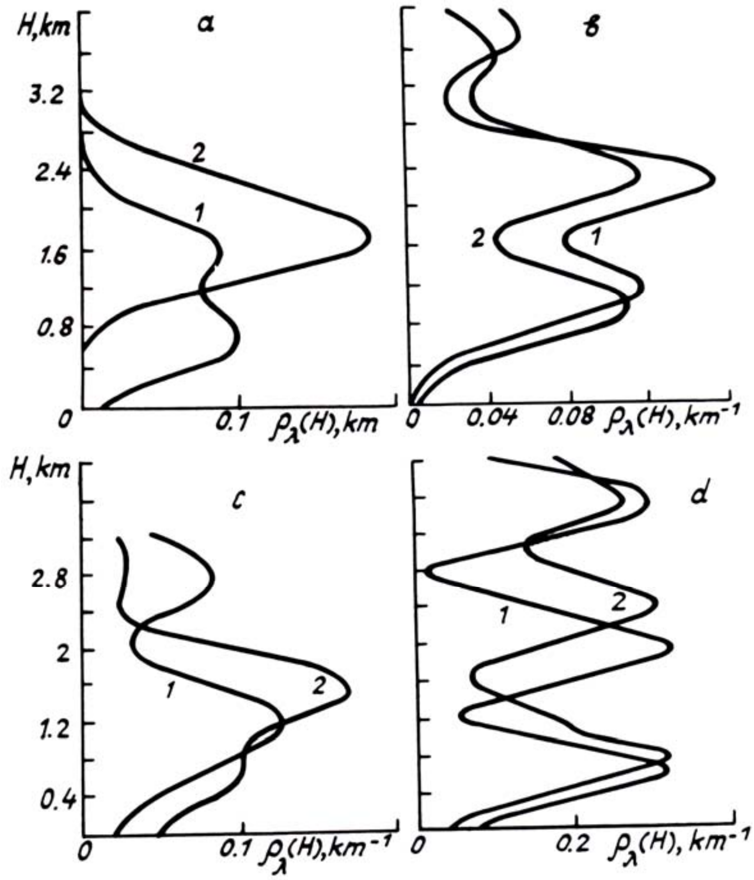

FIG. 2. Vertical profiles of the aerosol optical density: a) July 27, 1987, homogeneous haze, Cu clouds, 5-7 points. 12:00 LT, λ = 295 nm (1), λ = 322 nm (2). b) August 4, 1987, thin Ci clouds, haze. 11:40 LT, λ = 295 nm (1), λ = 322 nm (2). c) August 7, 1987, Sc clouds, haze, 13:10 LT, λ = 295 nm (1), λ = 322 nm (2). d) September 1985, cloudless, haze, λ = 322 nm, 10:30 LT, (1), 12:40 LT (2).

To increase data accuracy one might apply statistical averaging readings taken from different instruments during a whole day of observations (longer observational intervals can be considered too). For this purpose, however, one would need reliable preliminary data on the diurnal dynamics of the aerosol profiles and on the selectivity of the aerosol extinction in the UV range, etc. These data can only be obtained if the measurement accuracy were increased significantly. Therefore, the successful solution of these tasks calls for designing better instrumentation capable of narrowing the error margin to 1–2%. The new "Minsk-IM" modification of the UV photometer is expected to meet such demands.

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