VERTICAL DISTRIBUTION OF THE EXTINCTION COEFFICIENT OF UPPER LEVEL CLOUDS IN THE VISIBLE SPECTRAL RANGE

L.V. Kravets

Central Aerological Observatory, Dolgoprudny
Received February 28, 1990

Experimental studies of vertical profiles of the extinction coefficient of Ci-clouds in the visible spectral range with the help of a ground lidar are discussed in the present paper. The shape of the extinction coefficient profiles is found to differ for clouds with different lower boundary heights. Empirical correlations are obtained which describe the dependence of the extinction coefficient of Ci-clouds in the visible range on height.

The present paper is based on the results of complex experimental investigations of upper-level clouds which were carried out in spring-summer at the Zvenigorodsk Scientific-Research Station of the Institute of Atmospheric Physics of the USSR Academy of Sciences (IAP) in 1986, 1987, and 1989. Measurements were carried out for all types of clouds within the altitude range 5.5 to 12 km. The average altitude of the lower boundary of the upper-level clouds, observed at that time, was equal to 7700 m. The average cloud thickness was 1350 m; the maximum thickness was equal to 4400 m (at 12^h51^m, June 2, 1989).

Vertical profiles of the extinction coefficient $\beta(H)$ in the visible range in Ci-clouds were obtained with the help of a ground lidar developed by the Central Aerological Observatory. Data on the optical depth of Ci-clouds were used in the daytime measurements obtained by a spectrophotometer (IAP).[1] At night the lidar operated autonomously. A technique for reconstructing for $\beta(H)$ was proposed by the author of the present paper elsewhere.[2]

The main parameters of the lidar system are the following. The pulse energy of the transmitter at the wavelength λ = 1060 nm is 8 J and at λ = 530 nm it is 2 J. The pulse duration is equal to 30 ns. The beam divergence is 3 mrad and the receiving angle is equal to 1 mrad. The receiving antenna has a mirror of 0.3 m diameter. The upper and lower cloud boundaries were determined according to the method described in Ref. 3.

The spatial distribution of such optical parameters as the extinction coefficient of the visible radiation in Ci-clouds presents a complicated, variable picture. We carried out about 1200 lidar soundings of the upper-layer clouds. We determined the average profiles of the reconstructed extinction coefficient $\beta(H)$ for different altitudes of sounding of the lower boundary (and, consequently, temperatures) at different cloud thicknesses based on the obtained body of data. Figure 1 presents average relative profiles $\beta(H)$ from the lower to the upper boundaries of the cloud. The value of $\beta_{rel.un}(H) = \beta(H) / \langle\beta\rangle(H_u - H_1)$ [relative units] is plotted on the ordinate axis, where $\langle\beta\rangle$ is the average value of the extinction coefficient and $(H_u - H_1)$ is the cloud layer thickness. Obviously, $\int_{H_1}^{H_u} \beta \cdot dH = \langle\beta\rangle(H_u - H_1) = \tau$, where τ is the optical depth. The origin of the horizontal axis corresponds to the height of the lower boundary and its end, to that of the upper boundary. The profiles in Fig. 1 were obtained for clouds whose thickness varied between 1200 and 1800 m. We encountered this thickness range more frequently than others in the experiments. The average value of the thickness over the entire cycle of measurements lies in this range. In this sense the given distribution of $\beta(H)$ can be said to be typical. Note that the curves in Fig. 1 represent the average profiles $\beta(H)$ for a large number of cases. The individual profiles $\beta(H)$ have a variety of shapes.[3] The relative standard deviation $\sigma(\beta(H))/\beta(H)$, according to our calculational results, reaches 0.3–0.5 for different H. Therefore, the profiles plotted in Fig. 1 have meaning only for averaging over sufficiently large spaces.

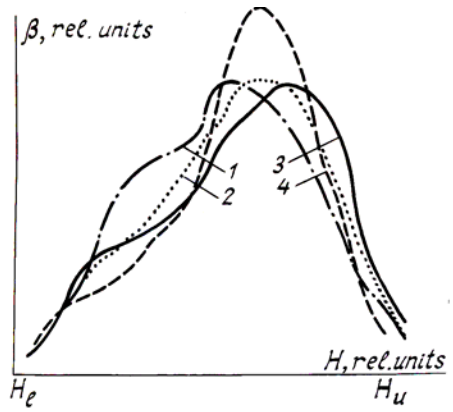

FIG. 1. The experimentally obtained vertical distribution profiles of the extinction coefficient of upper-level clouds in the visible spectral range.

0235-6880/90/08 818-04 $02.00

The curves in Fig. 1 differ one from the other. Curve 1, which is for clouds whose lower boundary varies from 6 to 7 km, depicts a distribution with a maximum near the average cloud height $(H_u - H_1)/2$, where H_u and H_1 are the heights of the upper and lower boundaries of the cloud. As the height of the lower boundary grows, the curves become asymmetric, i.e., the maximum of the distribution .shifts toward the upper cloud boundary (curves 2 and 3). For clouds whose lower boundary lies in the height interval 9–10 km (curve 4), these clouds were observed directly under the tropopause or partly above it the maximum of $\beta(H)$ shifts back toward the center of the distribution, in the process of which it attains its overall maximum value. This is apparently explained by the fact that the scattering mass of these clouds accumulates in a narrow layer directly under the tropopause.

The following empirical formula which describes the vertical profiles of the extinction coefficient of visible light in upper-layer clouds in the cloud thickness range from 1200 to 1800 m is proposed based on the experimental data:

$$\beta(H) = A\left[1 - \xi\right]^{2.56-0.125H_1} \cdot \left[e^{(0.83+0.4H_1)\xi} - 1\right],$$

$$\xi = \frac{H - H_1}{H_u - H_1}, \tag{1}$$

where H is the height (km). The parameter A can be determined if one knows the function describing the dependence of the average value of the optical depth τ on the height, for example, of the lower boundary of the cloud $\tau(H_1)$. Then we may write

$$\tau(H_1) = \int_{H_1}^{H_u} \beta(H)\, dH. \tag{2}$$

It is easy then to determine the parameter A from Eqs. (1) and (2).

Figures 2a, b, and c show the curves calculated by formula (1) and the experimental points taken from Fig. 1, for different values of H_1. Here one can see a good agreement if the upper boundary height H_u is less than H_t, where is the tropopause height. The vertical line segments in Fig. 2 show the maximum errors, determined from the experimental-model data obtained under daytime background conditions, as described in Ref. 3.

Note that the zeroing of the function $\beta(H)$, especially at the upper boundary, is extrapolatory. Under daytime background conditions the value of H_u, as measured by lidar sounding, underestimates the real value. However, for thin clouds with $\tau < 1$ (and, as a rule, it was specifically these clouds that were investigated in the experiments) this difference was not great.

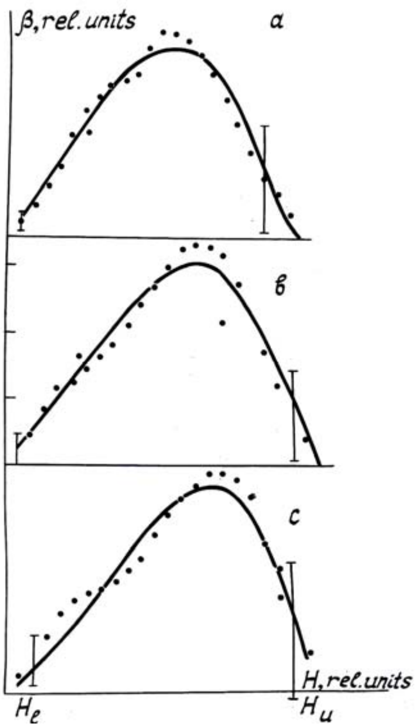

FIG. 2. Vertical distribution profiles of the extinction coefficient of visible light in upper-level clouds, obtained by formula (1): $H_1 = 6.5$ km *(curve a);* $H_1 = 7.5$ km *(curve b); and,* $H_1 = 8.5$ km *(curve c).*

Expression (1) for β can be transformed into a function of temperature t. Toward this end, during the experiments we determined the average temperature profile of the upper troposphere. The function $H(t)$ has the form

$$H(t) = 0.13|t| + 3.1. \tag{3}$$

Substituting relation (3) into formula (1), it ig easy to obtain a parametric relation for $\beta(t)$.

An important characteristic of cirrus clouds is their optical depth τ. On the basis of experimental . data Platt and Harshvardhan[4] have proposed the following functional dependence of the absorption coefficient for IR radiation σ_a on the mid-cloud temperature:

$$\sigma_a = B(t + t_0)^2, \tag{4}$$

where $B = 1.6 \cdot 10^{-4}$ for $t_0 = 82.5°C$. According to their estimates[4] the extinction coefficient of visible radiation is roughly twice σ_a. The empirical relation (4) can then be transformed to read

$$\langle\beta\rangle \simeq 3.2 \cdot 10^{-4}(t + t_0)^2. \tag{5}$$

The functional dependence (5) and our experimental values of the average extinction coefficient evaluated in eight-degree averaging intervals are plotted in Fig. 3. Our experimental values lie below the curve corresponding to the functional dependence (5) and can be fit quite well by a dependence of the form (5) if the factor before the parenthesis is changed to 2.4:

$$\langle\beta\rangle \simeq 2.4\cdot 10^{-4}(t + t_0)^2. \qquad (6)$$

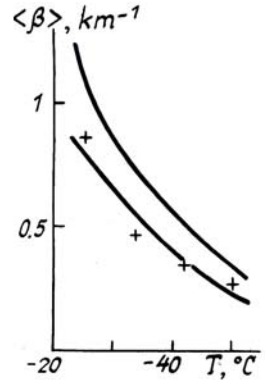

FIG. 3. Dependence of the average extinction coefficient in the upper-level clouds according to data taken from Ref. 4 (curve 1) and our experimental data (curve 2).

Proceeding from formula (6), it is fairly simple to obtain a final expression for the profile $\beta(t)$ The parameter A in Eq. (1) is found to be equal to

$$A = 1.85\cdot 10^{-3} \times$$

$$\times \frac{\int\limits_{|t_1|}^{|t_u|} (t + t_1)^2\, dt}{\int\limits_{|t_1|}^{|t_u|} (1 - \xi_t)^{2.17-0.016|t_1|} \{e^{(2.07+0.052|t_1|)\xi_t} - 1) dt}, \qquad (7)$$

$$\xi_t = \frac{|t| - |t_1|}{|t_u| - |t_1|},$$

where t_1 and t_u are the temperatures at the lower and upper boundaries of the cloud. Thus, expressions (1), (3), and (7) completely determine the profile $\beta(t)$.

Analyzing these results, we can draw the following conclusion. The shape of the vertical profile of the visible-range extinction coefficient in the upper-level clouds is different for different cloud heights and, consequently, for different temperatures. It was found that the maximum of the distribution $\beta(H)$ shifts toward the upper boundary with increasing cloud height (decreasing temperature). The shift of the maximum of $\beta(H)$ toward the upper boundary with increasing cloud height can be explained in the following way. The center of cloud particle generation is located near the upper boundary of a developed cloud. As the. cloud particles grow, the largest of them descend. Since in the higher clouds the particles are smaller, for vertical fluxes with the same velocity a smaller portion of the particles will fall. The maximum of $\beta(H)$, consequently, will be closer to the level of the initial center of particle generation. For particles located directly under the tropopause, the maximum of $\beta(H)$ is found to lie approximately at a level 0.3–0.5 km below it.

REFERENCES

1. P.P. Anikin and A.H. Shukurov, in: *Radiative Properties of Cirrus Clouds*, E.M. Feigel'son, ed. (Nauka, Moscow, 1989).
2. L.V. Kravets, Atm. Opt. **2**, No. 2, 146 (1989).
3. L.V. Kravets and V.N. Marinushkin, in: *Radiative Properties of Cirrus Clouds*, E.M. Feigel'son, ed. (Nauka, Moscow, 1989).
4. C.M.R. Platt and Harshvardhan, J. Geophys. Res: **9**, No. 9D, 11051 (1988).