DETERMINATION OF THE OZONE CONCENTRATION BY LIDAR SOUNDING AT THE WAVELENGTHS 308 AND 532 NM

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A method for sounding the ozone concentration at different wavelengths $\lambda_1 = 308$ *and* $\lambda_2 = 532$ nm *is briefly described. The method requires that the effect of the aerosol be correctly converted from* λ_1 *to* λ_2*. The accuracy with which the* O_3 *content is reconstructed is discussed based on mathematical analysis of the empirical data using different aerosol models.*

The method of laser sounding of atmospheric ozone at different wavelengths 308 and 532 nm is now employed for regular measurements of the ozone layer.[1,2] The method for processing the lidar data in order to determine the ozone concentration by this method[4] requires a large volume of calculations. In addition, the possibility of using for the calculation different optical models of aeroso1 and molecular scattering as well as the accuracy of such an estimate must be analyzed.

We shall calculate the ozone concentration $\rho(h)$ using the lidar data. It is well known that $\rho(h)$ can be determined, according to the lidar equation, as the sum of three components:

$$\rho_1(h) = \rho_1(h) + \rho_2(h) + \rho_3(h),$$

where

$$\rho_1(h) = \frac{1}{2\sigma\Delta h 10^{-5}} \ln \frac{\beta_\pi(h + \Delta h)}{\beta_\pi(h)} \tag{1}$$

$$\rho_2(h) = -\alpha \cdot 10^{-5}/\sigma \tag{2}$$

$$\rho_3(h) = \frac{1}{2\sigma\Delta h 10^{-5}} \ln \frac{N(h)h^2}{N(h + \Delta h)(h + \Delta h)^2}, \tag{3}$$

where $\rho(h)$ is given in the units $1/\text{cm}^3$; $\beta_\pi(h)$ is the volume backscattering coefficient, in km^{-1}; $\sigma = 1.4 \cdot 10^{-19}$ cm^2 is the absorption cross section of the ozone molecule at $\lambda = 308$ nm; h is the altitude, in km; α is the volume scattering coefficient, in km^{-1}; Δh is the spatial resolution, in km; and, $N(h)$ is the magnitude of the reflected signal for $\lambda = 308$ nm.

The volume backscattering coefficient β_π is the sum of the volume aerosol scattering coefficient $\beta_{\pi a}$ and the volume molecular scattering coefficient $\beta_{\pi m}$:

$$\beta_\pi(h) = \beta_{\pi a}(h) + \beta_{\pi H}(h). \tag{4}$$

The two terms on the right side of Eq. (4) are related with one another by the scattering ratio

$$R(h) = \frac{\beta_{\pi a}(h) + \beta_{\pi m}(h)}{\beta_{\pi m}(h)}. \tag{5}$$

The molecular scattering data for the wavelengths λ_x for which there are no model values of the molecular scattering coefficients are determined from the values of $\beta_{\pi m}$ that are known for the wavelength λ_0 with the help of the coefficient K_m expressing the relation between the molecular scattering at different wavelengths and being equal to $(\lambda_x/\lambda_0)^{-4}$

$$\beta_{\pi m}(\lambda_x) = K_m \beta_{\pi m}(\lambda_0). \tag{6}$$

The volume scattering coefficient in Eq. (2) is the sum of the volume molecular scattering coefficient α_m and the volume aerosol scattering coefficient α_a, which are related with $\beta_{\pi a} \cdot \beta_{\pi m}$ by the relations

$$\alpha_m(h) = \frac{8\pi}{3} \beta_{\pi m} \cdot \beta_{\pi m}(h); \tag{7}$$

$$\alpha_a(h) = \beta_{\pi a}(h)/q, \tag{8}$$

where q is the lidar ratio (in Ref. 5 the value $q = 0.03$ is used).

In the method of Ref. 3 the relation between the aerosol and molecular scattering at the wavelengths 308 and 532 nm is determined with the help of the correction factor $\mu = 1.8$. In this case

$$\beta_{\pi a308}(h) = \mu \cdot \beta_{\pi m532}(h) \cdot \{R(h) - 1\}. \tag{9}$$

Then the formulas (2) and (3) assume the form

$$\rho_1(h) = \frac{1}{2 \cdot \sigma \cdot \Delta h \cdot 10^{-5}} \times$$
$$\times \ln \frac{\beta_{\pi m}(h + \Delta h) \cdot \{1 + \mu \cdot (R(h + \Delta h) - 1)\}}{\beta_{\pi m}(h) \cdot \{1 + \mu \cdot (R(h) - 1)\}}; \tag{10}$$

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$$\rho_2(h) = -\left[\frac{8\pi}{3} + \mu\{R(h) - 1\}/0.03 \right] \frac{\beta_{\pi m}(h) \cdot 10^{-5}}{\sigma}. \quad (11)$$

The general relations presented above make it possible to estimate the ozone concentration from the lidar data. But the question of how sensitive the reconstruction of the ozone concentration from the lidar data is to the choice of the optical model of scattering, and primarily the aerosol scattering, remains open. To answer this question we shall study several variants.

Variant 1. We shall calculate the ozone concentration from the formulas (3), (10), and (11). It is most convenient to represent the factor μ in the form $\mu(h) = K_m \cdot K_a$, where the value K_m is known from the formula (6) and the coefficient K_a is constant along the entire vertical sounding path and ranges from zero (which corresponds to neglecting completely the aerosol scattering at the wavelength 308 nm) up to 1 (the aerosol scattering is known to be overestimated). The ozone concentration is calculated with the help of the model of molecular scattering (Refs. 7 or 5).

Variant 2. This method for calculating the ozone concentration[4] is based on the use of the aerosol scattering data from the average-cyclic model[6] and the formulas (3), (10), and (11), can be used to determine $\rho(h)$. Assuming that the correction factor μ changes with altitude and using the values of the volume backscattering coefficients given in Ref. 6 for the wavelengths 248, 347, and 530 nm, we calculate the factor $\mu(h)$ as follows:

$$\mu(h) = \frac{\beta_{\pi a248}(h) + \beta_{\pi a347}(h)}{\beta_{\pi a530}(h)}, \quad (12)$$

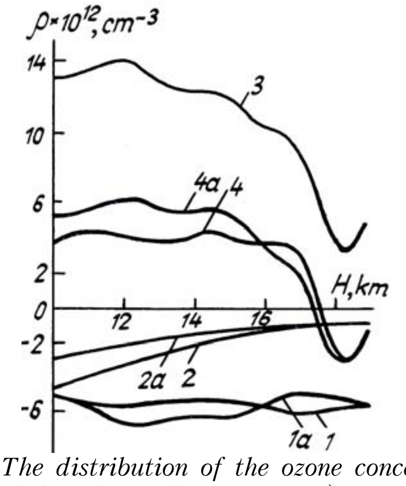

FIG. 1. The distribution of the ozone concentration (computed based on the variant 1). For K_a = 1, ρ_3 (1), ρ_2 (2), and ρ *(4); for K_a = 0, ρ_3 (1a), ρ_2 (2a),* ρ *(4a),* and ρ_3 *(3) (identical for all K).*

Figure 3 shows that the distributions $\rho(h)$ calculated based on the first (for K_a = 0.4) and third variants are virtually identical. The maximum variation in the values is equal to 5.2%.

where $\beta_{\pi a248}(h)$, $\beta_{\pi a347}(h)$, and $\beta_{\pi a530}(h)$ are the volume aerosol backscattering coefficients at the wavelengths 248, 347, and 530 nm ($\beta_{\pi a532} \approx \beta_{\pi a530}$), respectively. In this case the correction factor $\mu(h)$ ranges from 0.8 to 1.9.[4] The values of the molecular backscattering coefficient at 532 nm can be taken from Ref. 7.

Variant 3. The ozone concentration can be determined using the formulas (1)–(3) with the help of McClatchey's model, for which the values of volume aerosol and molecular scattering coefficients at a wavelength 337 nm are known.[5] Assuming that

$$\alpha_{a308}(h) \simeq \alpha_{a337}(h)$$

We can obtain the value of $\beta_{\pi a308}(h)$ from the formula (8). The values of $\beta_{\pi m337}(h)$ are the determined from the formula (7) and then converted to the wavelength 308 nm with the help of the formula (6).

The computational results presented in Figs. 1–5 make it possible to сотрете the vertical distributions of the ozone concentration calculated for the three variants based on the lidar data[2] at altitudes ranging from 8 to 17 km.

Figure 1 shows the curves of the altitude distribution of three hypothetical components of the ozone concentration for different values of the coefficient K_a. It is obvious that as K_a varies both the first and second components affect equally the curve of the total distribution (the third component is not related with the coefficient K_a).

Figure 2 shows the curves of the distribution of the ozone concentration with the coefficient K_a ranging from 0 to 1. The maximum change in the profile of the concentration in this case is equal to 32% at an altitude of 12 km and the minimum change is equal to 0 at an altitude of 16 km.

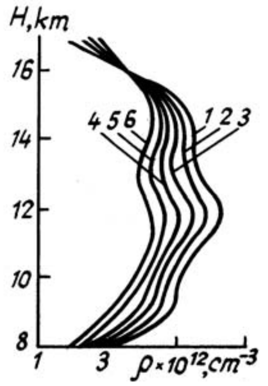

FIG. 2. The distribution of the ozone concentration (calculation based on the variant 1): K_a = 0 (1), 0.2 *(2),* 0.4 *(3),* 0.6 *(4),* 0.8 *(5), and* 1 *(6).*

The curves of the distributions of the ozone concentration calculated according to the first and second variants (Fig. 4) are also identical, with the exception of the region 9–11 km, where a deviation of 18% in the direction of lower concentration is observed. In addition, the change in the profile of the ozone concentration in the calculation based on the use of the data from the average-cyclic model is due to variations of the backscattering coefficients, which can reach hundreds of percent depending on the correct prediction of the chemical composition and, correspondingly, of the optical constants of the aerosol.

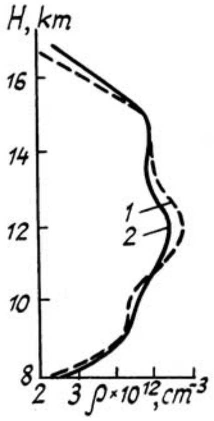

FIG. 3. The distribution of the ozone concentration calculated based on the variant 3 (1) and the variant 1 (2) for K_a = 0.4.

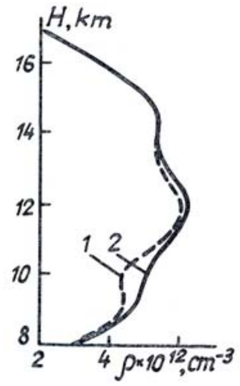

FIG. 4. The distribution of the ozone concentration calculated for the variant 2 (1) and the variant 1 (2) for K_a = 0.1.

Figure 5 shows curves of the altitude distribution of the ozone concentration calculated in the second variant taking into account the standard deviations ($+\delta\beta_a$) of the volume backscattering coefficients at λ = 532 nm.[6] The largest spread in the values of the distributions $\rho(h)$ taking into account the spread ($\pm\delta\beta_a$) is observed in the altitude range 9–11 km. The maximum deviation at an altitude of 10 km for a negative correction ($-\delta\beta_a$) is equal to 110%. For the positive correction ($+\delta\beta_a$) the maximum deviation is equal to 16%. When the ozone concentration is calculated using the values of $\beta_a(h)$ with the corrections $+\delta\beta_a(h)$ the curve of the distribution $\rho(h)$ is identical to the curve $\rho(h)$, calculated according to the first variant for K_a = 0.1.

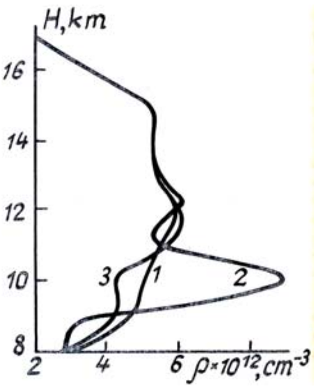

FIG. 5. The distribution of the ozone concentration calculated for the variant 2: 1) for + $\delta\beta_a$, 2) for $-\delta\beta_a$, and 3) for $\delta\beta_a$ = 0.

The analysis presented shows that the calculation of vertical distribution of the ozone concentration, performed based on lidar measurements using the correction for the ratio of scattering from the region λ = 532 nm on the region λ = 308 nm (the variant 1), is in good agreement with the calculation of $\rho(h)$, performed for model values of the scattering coefficients (the variants 2 and 3), if the value of the coefficient K_a is chosen from the range 0.1–0.4. As one can see from Fig. 2, changing the coefficient K_a by 0.2 results in a maximum change a of 3% in the computed values of $\rho(h)$. This does not exceed maximum discrepancy between the values of $\rho(h)$ calculated for the variant 1 and the values of $\rho(h)$ calculated according to other variants. Thus in calculating the ozone concentration K_a can be set equal to the average value from the interval presented above, namely, K_a = 0.25 and the first variant of the calculation can be used to reconstruct the ozone concentration from the lidar data.

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