ATMOSPHERIC OPTICAL DEPTH DETERMINATION FROM MEASUREMENTS OF THE THERMAL RADIATION ANGULAR DISTRIBUTION

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This paper discusses the results of measurements of angular distributions of the thermal radiation emitted by the Earth's surf ace-atmosphere system in the spectral region 9 to 18 μm. The separation of contributions of the atmosphere and the Earth's surface to the outgoing radiation is achieved by extrapolating to zero air mass. In determining the atmospheric emission spectra, continuous and selective absorption by atmospheric gases is taken into account. Measurement results are compared with model calculations made using atlases of spectral lines.

Spectroradiometric data obtained in the transmission window at 11.1 μm and within the water vapor absorption band at 13 μm made it possible to determine the optical depth of the atmosphere and to separate out the contribution due to attenuation of radiation by aerosols.

The problem of Atmospheric optical depth ($\tau_{\Delta\nu}$) determination in the 8 to 13 μm spectral region is closely related to thermal sounding of the surface-atmosphere system. A reliable account of $\tau_{\Delta\nu}$ variations is needed to accurately determine the system parameters at the lower boundary of the atmosphere.[1] However, insufficient knowledge of the light absorption by different aerosol fractions complicates the account of variations of the radiation extinction in the 8 to 13 μm spectral region. In particular, it is difficult to extract the contribution of the optically-active submicron fraction from the total radiation extinction, which also includes absorption by water vapor.[2]

In particular, it was found on the basis of the specially developed "minimum points" method[3] that the minimum effective absorption coefficient, interpreted as the maximum water vapor absorption coefficient, has a negligible dependence on the partial pressure of water vapor e and on the temperature T. This conclusion contradicts the data in Refs. 4–7. One of the reasons for this disagreement lies in the fact that for solar measurements of the spectral transparency along slant paths, the transmission function P_ν is associated with the integrated water vapor content over the entire atmospheric column, but, at the same time, the peculiarities of the vertical structure of $P_\nu(\zeta)$, where $\zeta = p/p_0$ is the normalized pressure, are smoothed out, thus becoming inaccessible for analysis.

Determination of only one of the optical depth parameters $\tau_{\Delta\nu}$, for instance, the water vapor content $w(\zeta)$, leads to an uncertainty in $\tau_\nu(\zeta)$ due to variation of the other factors whose importance increases with decrease of $w(\zeta)$. Thus, to determine the region of variation of τ_ν in the real atmosphere it is expedient to carry out profile measurements of the optical depth up to an altitude of 3–5 km, because of the fast decrease of $w(\zeta)$ with height under cloudless conditions.

In the present paper we consider a technique for determining the optical depth $\tau_{\Delta\nu}(\zeta)$ and the integrated depth of the total atmospheric column $\tau^*_{\Delta\nu}$ in the 10 to 12 μm spectral region. The values of $\tau^*_{\Delta\nu}$ were obtained from measurements of the upwelling ($I^{\uparrow}_{\Delta\nu}(\theta)$) and downwelling thermal radiation intensity ($I^{\Phi}_{\Delta\nu}(\theta)$) obtained from aircraft, ship, and satellite data.[8–11]

DETERMINATION OF THE OPTICAL DEPTH $\tau_{\Delta\nu}$ USING AIRCRAFT MEASUREMENT DATA

A study of the transformation of radiation in the atmosphere with altitude was carried out during 1973–1980. The equipment complex, which was mounted onboard an IL-14 airplane, included a radiometer which was capable of detecting radiation in the 10.5–12 μm spectral region,[8] a 0.53 μm backscattering nephelometer, temperature and humidity gauges, and also an A3-5 optical particle counter during one of the expeditions.[2]

The intensities of downwelling $I^{\Phi}_{\Delta\nu}(t,\theta)$ and upwelling $I^{\uparrow}_{\Delta\nu}(t,\theta)$ radiation at the level t along the direction θ are represented as follows:

$$I^{\downarrow}_{\nu}(t,\theta) = \int_0^t B_\nu[T(\xi)]\frac{d}{d\xi} P_\nu(t,\xi,\theta)d\xi \tag{1}$$

$$I^{\uparrow}_{\nu}(t,\theta) = B_\nu(T_s)P_\nu(t,1,\theta) - \int_1^t B_\nu[T(\xi)]\frac{d}{d\xi} P_\nu(t,\xi,\theta)d\xi - r_\nu(\theta)P_\nu(t,1,\theta)[B_\nu T_s) - T^{\downarrow}_\nu(1,\theta)]. \tag{2}$$

Here $B_\nu[T(\zeta)]$ and $B_\nu(T_s)$ are the Planck function at the air temperature $T(\zeta)$ and at the surface temperature T_s, respectively; $P_\nu(t, \zeta, \theta)$ is the transmission function between the levels t and ζ; and $r_\nu(\theta)$ is the reflection coefficient of the surface.

The transmission function $P_\nu(t, \zeta, \theta)$ is determined from the optical depths of the water vapor continuum absorption $m\tau^k_\nu(t, \zeta)$, the aerosol extinction $m\tau^a_\nu(t, \zeta)$, and the selective molecular absorption $\tau^c_\nu(t, \zeta, \theta) = \sum_i \alpha_i[m\tilde{u}_i(t, \zeta)]^{\beta_i}$, where $\alpha_i(\nu)$ and $\beta_i(\nu)$ are the coefficients for the i-th gas with mole fraction $\tilde{u}_i$, $m = \sec\theta$, and

$$P_\nu(t,\xi,\theta) = \exp\left\{-m\tau^c_\nu(t,\xi) - m\tau^a_\nu(t,\xi) - \sum_i \alpha_i[m\tilde{u}_i(t,\xi)]^{\beta_i}\right\} . \quad (3)$$

The technique for determining the optical depths $\tau_{\Delta\nu}(t, 0)$ and $\tau_{\Delta\nu}(t, 1)$ consists of measuring the altitude profiles $I^{\downarrow}_{\Delta\nu}(\zeta, \theta)$ and $I^{\uparrow}_{\Delta\nu}(\zeta, \theta)$ during descent and ascent of the airplane, respectively. It follows from expressions (1) and (2) that when the absorption is mainly proportional to the air mass $m = \sec\theta$ in the case when $r_{\Delta\nu}(\theta) = 0$, variation of the height $\Delta z_j^{j+1}(\Delta\zeta)$ leads to an increase in the optical depth

$$m\Delta\tau_{\Delta\nu}(\Delta z_j^{j+1}) = [I_{\Delta\nu}(z_{j+1},\theta) - I_{\Delta\nu}(z_j,\theta)] / [B_{\Delta\nu}[T(\tilde{t})] - I_{\Delta\nu}(z_j,\theta)], \quad (4)$$

where $I_{\Delta\nu}(z_j, \theta)$ is determined by Eqs. (1) and (2) for down- and upwelling radiation, respectively, and $T(\tilde{t})$ represents the mean temperature of the layer. The use of Eq. (1) in measurements of $\Delta\tau_\nu(t, 0)$ is preferable because it eliminates the effect of surface inhomogeneities in $B_{\Delta\nu}(T_s)$ and $r_{\Delta\nu}(\theta)$ and lightens the requirements on the range of signal variation and linearity of the radiometer.

If the values of $\Delta t_{\Delta\nu}(\Delta z)$ are compared with the water vapor content Δw, the measurement results can be characterized by the effective absorption coefficient $k^{\exp}_{\Delta\nu} = \Delta\tau_{\Delta\nu}(\Delta z) / \Delta w(\Delta z)$. The dependence of $k^{\exp}_{\Delta\nu}$ on the water vapor pressure e is shown in Fig. 1 for atmospheric layers of 0.5 km thickness. Here also are plotted values of $k^{\exp}_{\Delta\nu}$, taken from shipborne measurements of $I^{\downarrow}_{\Delta\nu}(1, \theta)$, against the water vapor pressure e at the bottom of the atmospheric column. It can be seen from Fig. 1 that within the errors of measurement the least-valued results can be approximated by the linear dependence

$$k^{(\min)}_{\Delta\nu}(e,T) = k^{(1)}_{\Delta\nu}(T) + k^{(2)}_{\Delta\nu}(T)\cdot e$$

with $k^{(1)}_{\Delta\nu} = 0.05$ cm^{-1}, and $k^{(2)}_{\Delta\nu} = 7.5$ cm^{-1}atm^{-1}. These values correspond to the temperature range $T(\zeta) = 270$–293 K for heights ranging from 0 to 3 km. Accounting for a temperature dependence of (–2%K^{-1}) [Refs. 4, 14–16] and reducing to a referenmce temperature of 296 K gives $k^{(1)}_{\Delta\nu}(296) = 0.025$ cm^{-1} and $k^{(2)}_{\Delta\nu}$ (296) = 8.1 cm^{-1}atm^{-1}. The values correspond to the spectral region 10.5–12 μm, and in order to compare them with k_ν measurements in the transparency microwindows of a few cm^{-1} width, the selective absorption should be subtracted. The latter is estimated to be 15–20% for the given range, which gives $k^{(1)}_\nu = 0.02$ cm^{-1} and $k^{(2)}_\nu = 7.07$ cm^{-1}atm^{-1}.

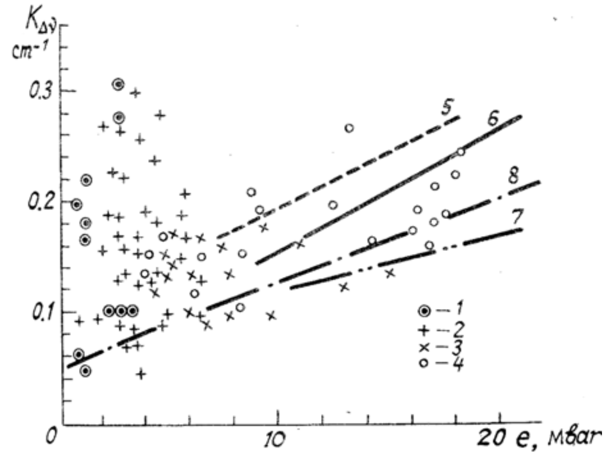

FIG. 1. Dependence of the effective absorption coefficient $K_{\Delta\nu}$ on the water vapor partial pressure e. Curves 1–3 correspond to airborne measurements at air temperatures: 1) –10+0°C, 2) 0+10°C, 3) 10–20°C, 4) shipborne measurements, 5–6) the dependence $K_{\Delta\nu}(e)$ determined in Refs. 4 and 13, respectively, 7) the region of minimum values of $K_{\Delta\nu}(e)$ [Ref. 13], 8) minimum values based on the present data, taking into account the error band $\Delta K = \pm 0.02$ cm^{-1}.

The values of $k^{(1)}_{\Delta\nu}$ and $k^{(2)}_{\Delta\nu}$ are approximate ones, with an error of about 0.02 cm^{-1}. A more rigorous approach requiring the calculation of selective molecular absorption In each experimental realization is described below.

The nonlinear method„ of calculating the frequency-selective optical depth $\tau^c_{\Delta\nu}$ is the most accurate one, but its application to each concrete meteorological situation requires large amounts of computer time. Therefore, an analytical depth $\tau^c_{\Delta\nu}[\zeta, w(\zeta), T(\zeta)]$ on the content of the main absorbing component in the transmission window - water vapor — was found. The calculations of $\tau^c_{\Delta\nu}$ were made using different atmospheric models and an atlas of spectral line parameters[17,18]

$$\tau_{\Delta\nu}[\zeta, w(\zeta), T(\zeta)] = \alpha_{\Delta\nu}[\zeta, w(1), T(\zeta)][mw(\zeta)]^{\beta_{\Delta\nu}[\zeta, T(\zeta)]} . \quad (5)$$

The coefficients $\alpha_{\Delta\nu}$ and $\beta_{\Delta\nu}$ are as follows:

$$\alpha_{\Delta\nu}[\xi, w(1), T(\xi)] = c_1\left[\frac{T(\xi)}{T_0}\right]^{c_2} \times$$
$$\times \exp\left[-c_3 - c_4\frac{w(1)T(1)}{T_0}\right](1-\xi);$$
$$\beta_{\Delta\nu}[\xi, T(\xi)] = c_5\left[\frac{T(\xi)}{T_0}\right]^{-c_6}(1-c_7\sqrt{1-\xi}).$$

For the spectral region 10.5–11.5 μm the values of the coefficients c_1 are $c_1 = 0.0393$, $c_2 = 5.488$, $c_3 = 3.3$, $c_4 = 0.6$, $c_5 = 0.5676$, $c_6 = 2.067$, and $c_7 = 0.64$. The expression $w(1)T(1)/T_0$ in the argument of the exponential is a characteristic parameter of the atmospheric model. The accuracy of the parametric representation of $\tau_{\Delta\nu}$ by expression (5) is about 0.001.

Talking account of both the selective transmission function. and the continuum extinction, the expression for the difference in the values of the downwelling radiation $\Delta t_{\Delta\nu}(\zeta_1, \zeta_2, m)$ at the reduced pressure levels ζ_1 and ζ_2 takes the form:

$$\Delta I_{\Delta\nu}(\xi_1, \xi_2, m) = \sum_{n=0}^{N} \tilde{c}_n [m\Delta w(\Delta\xi)\ k^b_{\Delta\nu}(\xi)]^n. \qquad (6)$$

The first few coefficients $\tilde{c}_n$ $(n \le N = 2)$ are:

$$\tilde{c}_0 = [B_{\Delta\nu}(T(\bar{\xi})) - I_{\Delta\nu}(\xi_1, m)]\ [1 - P^c_{\Delta\nu}(\Delta\xi, m)];$$
$$\tilde{c}_1 = [B_{\Delta\nu}(T(\bar{\xi})) - I_{\Delta\nu}(\xi_1, m)]P^c_{\Delta\nu}(\Delta\xi, m)] - \frac{1}{2}\ B_{\Delta\nu}(T(\bar{\xi}))$$
$$\tilde{c}_2 = -\frac{1}{2}\ [B_{\Delta\nu}(T(\bar{\xi})) - I_{\Delta\nu}(\xi_1, m)]P^c_{\Delta\nu}(\Delta\xi, m)] + B_{\Delta\nu}(T(\bar{\xi})) \times$$
$$\times [1 - P^c_{\Delta\nu}(\Delta\xi, m)]\frac{1}{3!};$$

where $\Delta\zeta = \zeta_2 - \zeta_1$, $\Delta w(\Delta\zeta)$ is the water vapor content in the layer $\Delta\zeta$ and $k^{\delta}_{\Delta\nu}(\zeta) = k^{\delta}_{\Delta\nu}(\zeta, T, e)$ is the Bouguer continuum extinction coefficient.

The error in the Bouguer extinction coefficient $k^{B}_{\Delta\nu}(\zeta)$ can be estimated using expressions (4) and (6). The above value $\Delta k_{\Delta\nu} = 0.02$ cm^{-1} corresponds to a measurement error in the radiative temperature ΔT_r of 0.15 K for values of $I_{\Delta\nu}(\zeta_1, \zeta_2, m)$ in the air mass range $m = 2$ to 3 and for water vapor content $\Delta w \ge 0.1$ cm in a layer of thickness $\Delta h = 0.5$ km, which is typical in the middle latitudes. Comparison of expressions (4) and (6) reveals that the contribution of selective absorption increases with increase of the altitude h above 3 km and decrease of the humidity $\Delta W(\Delta\zeta)$.Therefore, to provide the required accuracy of $k^{B}_{\Delta\nu}(\zeta)$, it is necessary according to Eq. (6) that the errors in $\Delta k^{B}_{\Delta\nu}$ and ΔT_r be coordinated, and the values of the air mass $m = \sec\theta$ and of $\Delta\zeta$ be increased.

In order to determine the residual optical depth $\Delta\tau^{o}_{\Delta\nu}(\Delta\zeta)$ of the layer $\Delta\zeta$ the calculated radiation intensity $\Delta I^{r}_{\Delta\nu}(\zeta_1, \zeta_2, m)$ for the molecular atmosphere was compared with the data of layer-by-layer measurements $\Delta I_{\Delta\nu}(\zeta_1, \zeta_2, m)$. The values of $\Delta I^{r}_{\Delta\nu}(\zeta_1, \zeta_2, m)$ were calculated from real air temperature $T(\zeta)$ and humidity $w(\zeta)$ profiles for each experimental realization. As a result the following representation of $\Delta\tau^{o}_{\Delta\nu}(\Delta\zeta)$ was found[18]:

$$\Delta\tau^{o}_{\Delta\nu}(\Delta\zeta) = \Delta\tau_{\Delta\nu}(\Delta\zeta) - \Delta\tau^{r}_{\Delta\nu}(\Delta\zeta),$$

where $\Delta\tau^{r}_{\Delta\nu}(\Delta\zeta)$ is the optical depth due to extinction by the molecular components.

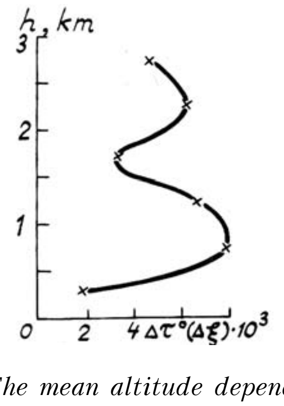

FIG. 2. a) The mean altitude dependence of the residual optical depth $\tau^{o}_{\Delta\nu}(h)$ in the spectral region 10.5–12 μm measured over Rybinsk reservoir and Lake Balkhash in August-October, 1976;

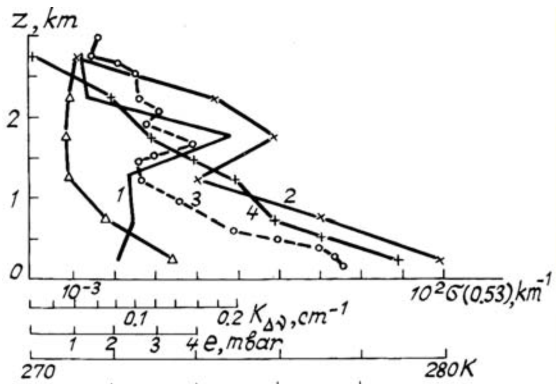

FIG. 2. b) The vertical distribution of the values of the coefficients $K_{\Delta\nu}(z)$ and σ(0.53), 20.09.76, Rybinsk reservoir. Curve 1 represents the dependence $K_{\Delta\nu}(z)$ in the spectral region 10.5–12 μm; curve 2 is the altitude dependence of the backscattering coefficient σ at the wavelength 0.53 μm; curve 3 is the particle number density n; curves 4 and 5 show the temperature profile T(z) and the water vapor partial pressure profile, respectively.

In Fig. 2a the average vertical profile of the residual optical depth $\tau^{o}_{\Delta\nu}(h)$ is shown for the spectral region 10.5–12 μm and for altitudes from 0.1 to 3 m. The measurements were carried out over Rybinsk reservoir and Lake Balkhash under cloudless conditions in 1976. The data presented in Fig. 2a clearly reveal the stratified behavior of the $\tau^{o}_{\Delta\nu}(h)$ profile, on the basis of which it is possible to interpret $\tau^{o}_{\Delta\nu}$ as the radiation extinction due to aerosols. Note that the altitude interval 2–2.5 km, where one of the $\tau^{o}_{\Delta\nu}(h)$ maxima appears in autumn, corresponds on the average to the level at which the condensation of atmospheric water vapor occurs.

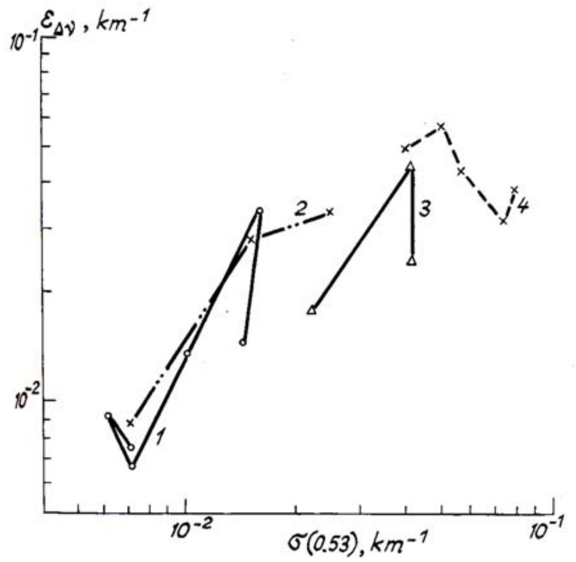

FIG. 3. The dependence of the aerosol extinction coefficient ε_ν on $\sigma(0.53)$ in the spectral region 10.5–12 μm: 1–3) measurements over Rybinsk reservoir on 10.09.76, 8.09.76, and 13.09.76, respectively; 4–5) the same, near Lake Balkhash, on 20 and 21.09.76.

The vertical sections of $I^{\downarrow}_{\Delta o}(\zeta, \theta)$ allow one to identify the atmospheric layers where $k^{\exp}_{\Delta\nu}$ increases, which correlates with the increase of the backscattering coefficient $\sigma(0.53)$ and the particle number density n. In Fig. 2b an example of the dependence of $k^{\exp}_{\Delta\nu}(\zeta)$ on height is presented, which demonstrates the existence of the aerosol layer at altitudes near 2 km. The proof of this lies in the simultaneous change of $k^{\exp}_{\Delta\nu}(\zeta)$, $\sigma(0.53)$, and n. Using the difference $\Delta\tau^{o}_{\Delta\nu}(\Delta z)$, it is possible to calculate the volume extinction coefficient $\varepsilon_{\Delta\nu}$, which mainly characterizes the aerosol volume extinction coefficient in the spectral region 10.5–12 μm. The results of such calculations made using the data In Fig. 1 are shown in Fig. 3 in the form of the dependence of $\varepsilon_{\Delta\nu}$ on $\sigma(0.53)$. It follows from Fig. 3 that in the range $5\times10^{-3} \le \sigma \le 1\times10^{-1}$ km^{-1} the values of $\varepsilon_{\Delta\nu}$ and $\sigma(0.53)$ lie within a factor of 2 of each other. Thus, the measurements of the vertical profiles of $I^{\downarrow}_{\Delta o}(\zeta, \theta)$ allowed us to separate out the water vapor and aerosol contributions in different ranges of the values of $\Delta\tau_{\Delta\nu}$ and $K_{\Delta\nu}$.

OPTICAL DEPTH DETERMINATION USING ANGULAR DISTRIBUTIONS OF THE RADIATION INTENSITY

The profile of aerosol optical depth $\tau^{a}_{\nu}(\zeta)$ can be determined from the angular distribution $I^{\uparrow}_{\nu}(m)$ if the altitude dependences of temperature $T(\zeta)$ and humidity $w(\zeta)$ are known. Let us represent the atmospheric transmission function $P_\nu(\zeta, m)$ as

$$P_\nu(\xi, m) = P^{g}_{\nu}(\xi, m)\, P^{a}_{\nu}(\xi, m),$$

where $P^{g}_{\nu}(\zeta, m)$ is the transmission function of water vapor and other gaseous components and is $P^{a}_{\nu}(\zeta, m)$ the aerosol transmission function. Let us denote by $I_\nu(m)$ and $\bar{I}_\nu(m)$ the measured intensity of the outgoing radiation, and the intensity calculated using known profiles $T(\zeta)$ and $P^{r}_{\nu}(\zeta, m)$, respectively. Then $\tilde{I}_\nu(m) = \bar{I}_\nu(m) - I_\nu(m)$.

It follows from Eq. (2) under the conditions $m\tau^{a}_{\nu}(\zeta) \ll 1$ and $r_\nu = 0$ that

$$\tilde{I}_\nu(m) = m\int_0 \frac{dB_\nu[T(\xi)]}{d\xi} P^{g}_{\nu}(\xi, m)\, \tau^{a}_{\nu}(\xi) d\xi \,. \tag{7}$$

To determine $\tau^{a}_{\nu}(\zeta)$, measurements of $\tilde{I}_\nu(m)$ were carried out in the vicinity of 11.1 μm at three zenith angles: 0, 48, and 54°, from the satellite "Kosmos-1151." The intensity $I_\nu(\theta = 0)$ at the wavelength 12.9 μm (Refs. 10 and 11) was also included in system of equations (7). The temperature profile required for the solution of system (7) was determined using the nearest radiosonde data, and the humidity profile $w(\zeta)$ was calculated using measurements in the 18 μm absorption band of water vapor.[19]

The solution of system (7) corresponds to the minimum of the functional:

$$F = \sum_{i,j} g_i [\tilde{I}^{\exp}_{\nu j}(m_i) - I^{cal}_{\nu j}(m_i)]^2, \tag{8}$$

where $g_j = \Delta^2 / \sigma^2_j$ is the weighting function for the j-th channel, Δ is the discretization step, and σ^2_j is the variance of the error in the j-th channel, $i = \overline{1, 3}$; j = 1, 2. The minimum of F is sought using such properties of $\tau^{a}_{\nu}(\zeta)$ as its positivity and monotonicity.[20,21]

Examples of the determined functions $\tau^{a}_{\nu}(\zeta)$ are presented in Fig. 4. From these it is obvious that the distribution $\tau_\nu^a(\zeta)$ reveals the existence of an attenuating layer near the tropopause, which can be explained for the considered realizations by the presence of the layer recorded in the synoptic observations, and consisting of semi-transparent cirrus-like haze, or thin C_i clouds.

The second approach to the determination of the atmospheric optical depth consists in approximating $B_\nu[T(\zeta)]$. If the surface temperature T_s is known (methods for determinating it are described in Refs. 10 and 11), in the case $r_\nu = 0$ one has for the Bouguer transmission function:

$$\hat{y}_\nu(m) = m\tau_\nu^* \int_0^1 \hat{b}_{\Delta\nu}(\kappa)\exp(-m\tau_\nu^*\kappa)d\kappa \quad (9)$$

where

$$\hat{y}_\nu(m) = 1 - I_\nu(m)/B_\nu(T_s),$$

$$\hat{b}_\nu(\kappa) = 1 - B_\nu(\kappa)/B_\nu(T_s);$$

τ_ν^* is the total optical depth, and $\kappa = \tau/\tau^*$ is the integration variable.

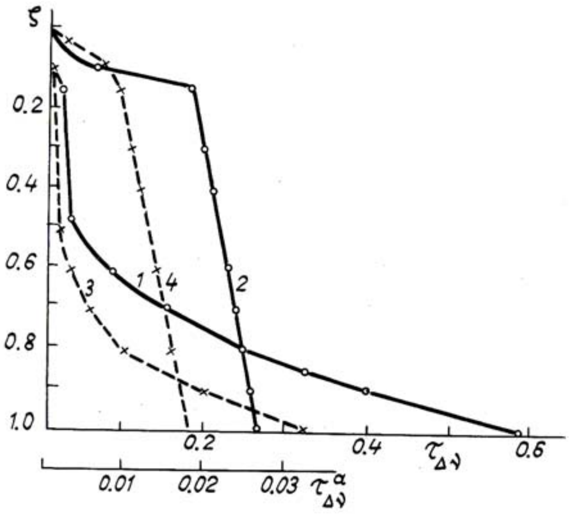

FIG. 4. Profiles of the total and aerosol optical depths $\tau_{\Delta\nu}$ and $\tau_{\Delta\nu}^a$: 1–3) the total depths in the tropics of the Indian and the Atlantic Oceans, 18.07.80 and 1.04.80; 2–4) profiles of the aerosol depths $\tau_{\Delta\nu}^a$ corresponding to the total depth $\tau_{\Delta\nu}$ profiles 1 and 3.

The normalized intensity $\hat{b}_\nu(\kappa)$ can be approximated as follows:

$$\hat{b}_\nu(\kappa) = \varphi_0(\kappa) + \sum_k c_k\varphi_k(\kappa);$$

$$\varphi_0(\kappa) = \begin{cases} c_1, & 0 \le \kappa \le \kappa_1 \\ c_1(\ln\kappa - \ln\kappa_1); & \kappa_1 < \kappa \le 1; \end{cases} \quad (10)$$

$$\varphi_k(\kappa) = c_k \sin k\pi\kappa$$

The representation of $\hat{b}_\nu(\kappa)$ in this form provides an approximation of the $\hat{b}_\nu(\kappa)$ profiles both containing and not containing temperature inversions $T(\zeta)$. The solution of system (9) for different m is sought as a minimum of the functional $F(\tau_\nu^*)$:

$$F(\tau_\nu^*) = \| \hat{y}^{\exp}(\tau_\nu^*, m) - \hat{y}^{\text{cal}}(\tau_\nu^*, m) \|, \quad (11)$$

where the superscripts exp and cal denote the experimental and calculated values, respectively, just as in expression (8). The solution is sought under the condition that $\hat{b}_\nu(\kappa) \ge 0$ as the minimum of those values of τ_ν^* which satisfy the inequality

$$\| \hat{y}^e(\tau_\nu^*, m) - \hat{y}^{\text{cal}}(\tau_\nu, m) \| \le \sigma_\nu,$$

To carry out the calculations using the described method, realizations were chosen for which the ocean surface temperatures T_0 determined using the angular method[10,11] did not differ by more than 0.5 K from the shipborne temperature measurements T_s. The atmospheric optical depths τ_ν^* determined using Eqs. (9)–(11) in the spectral region 10.5–11.5 μm were compared with the optical depths for the spectral region 18–19 μm (see Fig. 5). It can be seen from Fig. 5 that these values differ by an order of magnitude in these spectral intervals.

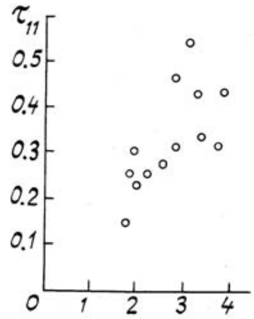

FIG. 5. The correlation between optical depths $\tau_{\Delta\nu}$ in the spectral regions 11.1 and 18–19 μm.

In Fig. 6 an example of the dependence of the discrepancy norm $r = \| \hat{y}(\tau_\nu^*, m) - \hat{y}^{\text{cal}}(\tau_\nu^*, m) \|$ on the optical depth t_ν^* is shown, which reveals the oscillatory character of the behavior of $r(T_\nu^*)$. The choice of the criterion $\tau_\nu^* = \tau_{\nu\,\min}^*$, for which the condition $r \le \sigma_1$ reflects the probabilistic character of the solution, is explained by the possible existence of several local minima of solution (11) and corresponds to the sense of regularization for a limited number of viewing directions m_i and basis functions φ_k in Eq. (10). The first local minimum

$r = 1.27\times10^{-3}$ mW/cm^2 · sr · μm at $\tau^*_\nu = 0.31$ in Fig. 6 corresponds to a radiation temperature discrepancy of 0.1 K.

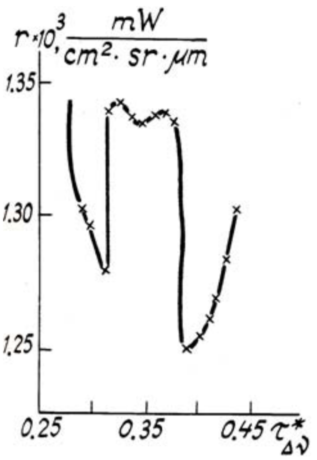

FIG. 6. Example of the dependence of the discrepancy norm (r) on optical depth $\tau^*_{\Delta\nu}$. The measurements were carried out on 9.04.1980 at coordinates φ = 29.7°N, λ = 47.2°U.

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