WAVELENGTH DEPENDENCE OF THE OPTICAL CHARACTERISTICS OF CLOUD LAYERS FROM THE OBSERVATIONS MADE AS PARTS OF POLEX–76 AND GAREX PROGRAMS

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The characteristics of transmission, reflection and absorption of radiation by stratus are calculated from the data of observations made as parts of the POLEX–76 (May 29, 1976) and GAREX (April 20, 1985) programs taking into account the illumination from below, i.e., from the underlying surface. The vertical profile of monochromatic (λ = 650 μm) *radiation fluxes in clouds is also retrieved from the data of observations made on April 20, 1985.*

1. WAVELENGTH DISTRIBUTION OF THE RADIANT ENERGY INFLUX AND OF THE EFFECTIVE COEFFICIENT OF ABSORPTION OF THE RADIATION FLUX BY CLOUD LAYERS

Let us apply the relations derived in Ref. 1 to the interpretation of the experimental data obtained in the Laboratory of short wavelength atmospheric radiation of the Leningrad State University onboard IL–14 and IL–18 aircrafts as parts of the POLEX–76 program performed over the Kara Sea on May 29, 1976 and of the GAREX program performed over Ladoga Lake on April 20, 1985.[2] In both cases stratus were observed. The thickness of the cloud layer was approximately 7.5 km (observations were carried out at altitudes of 0.2 and 8 km), and 1.5 km (observations were carried out at altitudes of 0.2 and 1.7 km) in the first and second cases, respectively. Zenith distances of the sun were approximately identical: $\cos Z_{\odot} \approx 0.57$ and $\cos Z_{\odot} = 0.65$ in the first and second cases. The underlying surface was covered with snow (lying on the ice) with very high albedo equal to 35–40% in the first and 45–65% in the second cases.

When sounding over Ladoga Lake on April 20, 1985, the measurements were carried out not only above and under the cloud layer, but also at the altitudes up to 5 km. They were used to obtain the monochromatic radiation characteristics (MRC) in the free atmosphere above the cloud layer.

During the time between the experiments under consideration the available spectral apparatus was essentially modernized.[3] The measurements on May 23, 1976 were carried out with the 20–μm step, and the smoothed curve was drawn through the MRC, corresponding to the wavelength regions without the molecular absorption bands ("continuous" spectrum). The measurements on April 20, 1985 were carried out with the 10–μm step. Absorption in the molecular bands of O_2, H_2O, and so on obviously affects the MRC; however, the above–indicated wavelength resolution is insufficient for adequate description of the shapes of the corresponding absorption bands. This deficiency is not critical, since in what follows we will consider the absorption in the "continuous" spectrum alone.

The upwelling and downwelling monochromatic radiation fluxes, albedo, budgets, and radiant energy influxes at fixed altitudes were given in Ref. 2. In this paper we will present only the data on additionally calculated parameters[1], i.e., the effective monochromatic absorption coefficient K, the transmission coefficient T, and the monochromatic albedo A of the cloud layers, as well as the absolute b and relative β radiant energy influxes (see Table I) in the free atmosphere above the cloud layer (April 20, 1985).

The radiant energy influxes in each atmospheric layer are shown in Figs. 1 and 2. Smoothed curves of the absorption in the "continuous" spectrum are shown in the same figures. Note that on May 29, 1976 the absorption was associated with the layer with $\Delta p \approx 620$ mbar, while the absorption in the free atmosphere was observed in the layer with $\Delta p \approx 240$ mbar and in clouds – in the layer with $\Delta p \approx 160$ mbar.

The absorption of the radiant energy in the "continuous" spectrum on April 20, 1985 in the atmospheric layer above the clouds was about 2–3 mW/cm^{2}μm and was approximately independent of the wavelength with slight rise in the region of the Chappeu absorption band of ozone (0.55–0.65 μm). The increase in the relative influx of radiant energy (Fig. 2) varies from 2% in the blue region (400–500 μm) to approximately 4% in the infrared region (800–900 μm). This effect is called the "red" absorption (obviously, the medium absorbing more intensively in the red region than in the blue region must acquire blue shade, therefore, let us call it "blue").

The absorption in the cloud layer, although it was thin, was much larger and selective: it reaches a maximum of approximately 8 mW/cm^{2}μm at a wavelength of 680 μm. The absorption in the atmospheric column is similar: it reaches a maximum of 11 mW/cm^{2}μm. The comparison of absorption in clouds and absorption above them taking into account the differences of layer thicknesses at wavelengths larger than 750 μm shows that the absorptance of the cloud layer is approximately two times greater than the absorptance of the cloudless atmosphere. This is evidently caused by the fact that in the cloud layer, whose thickness is equal to the thickness of the layer of the free atmosphere, the photons travel a longer distances untill they exit from the cloud layer and for this reason experience larger real absorption. The lower curve *6* in Fig. 1 represents the difference between the cloud layer absorption and the doubled absorption in the layer of free atmosphere (scaled to the layers of the same thickness with $\Delta p = 100$ mbar). The behavior of this curve, resembling the wavelength dependence of the chlorophyll absorption in this wavelength range, makes it possible to assume that in the cloud layer, in addition to the particles presented in the free atmosphere above the cloud, there were also particles of the organic origin with the above–indicated wavelength dependence of the absorptance.

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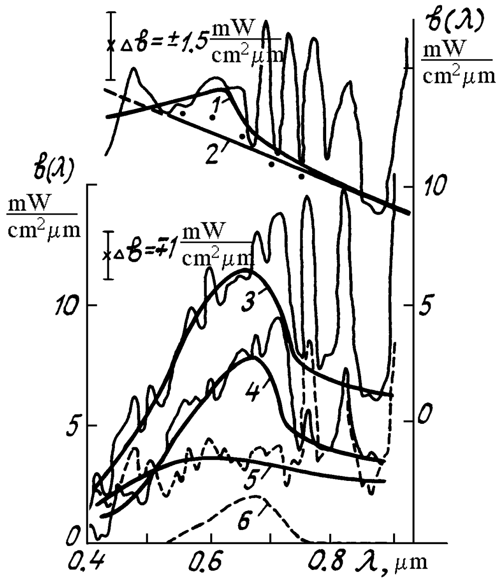

FIG. 1. Absolute radiant energy influxes b *in the cloudy atmosphere: 1) May 29, 1976. Cloud layer within the* 0.2–8.0 km *altitude range (*Δp = 620 mbar*); 2) The same layer without the Chappeu absorption band; 3) April 20, 1985. Layer of clouds and the atmosphere above them within the* 0.2–4.5 km *altitude range (*Δp = 400 mbar*); 4) April 20, 1985. Cloud layer within the* 0.2–1.7 km *altitude range (*Δp = 160 mbar*); 5) April 20, 1985. Atmospheric layer above the clouds within the* 1.7–4.5 km *altitude range (*Δp = 240 mbar*); and, 6) April 20, 1985. Difference between the influxes in the cloud layer and in the atmosphere (scaled to* Δp = 160 mbar*).*

The above–indicated peculiarities can be also seen in the curves (Fig. 2) of relative spectral influxes in the cloud layer (curve *3*) and in the atmosphere above it (curve *5*). In addition to the general rise from the blue to infrared regions varying from 1 to approximately 5%, the wide absorption band reaching 10% is manifested in the wavelength region 550–570 μm. Thus, the "blue" aerosol was present both in the cloud and in the atmosphere above it. As it has been already mentioned, the particles with the absorptance similar to the absorptance of organic particles were present in the cloud. Note that the increase in the absorptance with the wavelength is typical, for example, of graphite[4] and some other aerosols of mineral origin. To the point, clouds with such a wavelength dependence of the absorption, as it has been already indicated above, must have tints of blue when observating them from the ground, and this way really commonly observed.

The absorption of the radiant energy in the "continuous" spectrum in the cloud layer on May 29, 1976 was larger than on April 20, 1985 and was selective: it reached a maximum of about 14 mW/cm^{2}μm at a wavelength of 600 μm. The increase of the absorption in the wavelength region 550–650 μm can be caused by the ozone absorption in the Chappeu band. To check this assumption, let us analyze the curve of the radiant energy influx in the layer of the free atmosphere obtained over Ladoga Lake on April 20, 1985. If we subtract the above–indicated ozone absorption in the Chappeu band in the free atmosphere, converted to the same thickness of the atmospheric layer with Δp = 340 mbar, from the smoothed values of the radiant influx in the "continuous" spectrum obtained on May 29, 1976, the resulting difference will have the wavelength dependence close to the linear in the wavelength range 500–900 μm shown by straight line *2* in Fig. 1. This straight line in Fig. 1 decays with increasing the wavelength; however, passing over to the relative radiant energy influx (Fig. 2), we obtain the dependence, which is close to neutral or is slightly rising with wavelength (analogously to the case of clouds observed on April 20, 1985). As has already been noted above, either anthropogeneous aerosols or aerosols of organic origin (not completely burned "organic" in smogs, the pollen of plants and trees, and the like) can have such a wavelength dependence.

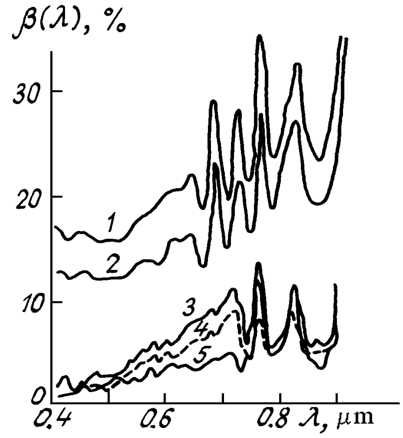

FIG. 2. Relative radiant energy influxes β *and effective absorption coefficients K in the cloudy atmosphere: 1) May 29, 1976.* β *within the* 0.2–8.0 km *altitude range (*Δp = 620 mbar*); 2) May 29, 1976. K for the same altitudes; 3) April 20, 1985.* β *within the* 0.2–1.7 km *altitude range (*Δp = 160 mbar*); 4) April 20, 1985. K for the same altitudes; and, 5) April 20, 1985.* β *within the* 1.7–4.5 km *altitude range (*Δp = 240 mbar*).*

Thus, summerizing the analysis of the curves, wee can formulate the following assumptions on the absorptance of aerosol particles, presented in the earth's atmosphere, in the above–indicated observation dates.

1) Over Ladoga Lake on April 20, 1985 the atmospheric absorption in the "continuous" spectrum in the visible was caused by "blue" absorbing aerosol and by the ozone absorption in the Chappeu band. The organic particles selectively absorbing the radiation in the wavelength region of the chlorophyll absorption band 550–750 mm were present in the cloud layer at altitudes lower than 1.7 km.

2) Over the Kara Sea on May 29, 1976 the absorption of the short–wave length radiation in the cloud layer was caused by the aerosol with the absorptance close to neutral (or slightly "blue") and by the absorption in the Chappeu band.

The reliability of these conclusions is completely determined by the error in the data shown in Fig. 1.

Wavelength dependences of the real absorption coefficients in the cloud layers for the above–considered observation dates are shown in Fig. 2 (curve *2* for observations made on May 29, 1976 and curve *4* for observations made on April 20, 1985). These curves lie under the corresponding curves of the relative radiant energy influx, keeping, on the whole, their peculiarities. The wavelength dependence on May 29, 1976 becomes more neutral, and on April 20, 1985 becomes less "red".

TABLE I. Spectral radiative characteristics of stratus.

	Observations made on May 29, 1976			Observations made on April 20, 1985						
λ, μm	A, %	T, %	K, %	A, %	T, %	K, %	A_{cl}, %	$B\ \frac{\text{mW}}{\text{cm}^2\cdot\mu\text{m}}$ ΔH = 1.7–4.5 km	β, % ΔH = 1.7–4.5 km	$B\ \frac{\text{mW}}{\text{cm}^2\cdot\mu\text{m}}$ ΔH = 0.2–4.5 km
1	2	3	4	5	6	7	8	9	10	11
400				76.8	22.2	0.9	53.4	0.7	0.7	1.8
410	22.1	65.0	12.9	77.9	21.7	0.4	56.7	1.8	1.6	2.4
420				76.1	23.8	0.1	56.8	3.0	2.8	3.1
430	22.6	65.3	12.1	75.7	24.1	0.2	58.1	1.6	1.5	2.0
440				75.2	24.5	0.3	59.2	1.4	1.2	1.9
450	24.4	65.9	12.7	73.9	24.3	1.8	59.3	1.7	1.3	4.5
460				73.5	25.3	1.2	60.1	2.7	2.0	4.8
470	25.0	62.5	12.5	72.4	26.3	1.3	60.1	3.5	2.6	5.7
480				71.4	27.3	1.3	60.1	4.2	3.1	6.4
490	25.0	66.2	11.8	69.8	29.2	1.0	59.4	2.8	2.2	4.4
500				70.1	28.8	1.1	60.5	3.5	2.7	5.3
510	20.5	67.6	11.9	69.7	28.2	2.1	60.8	3.5	2.8	6.7
520				69.2	28.7	2.1	61.0	2.7	2.3	5.9
530	19.5	68.3	12.0	68.8	28.9	2.3	61.2	2.1	1.7	5.6
540				68.2	28.8	3.0	61.1	2.3	1.8	7.1
550	19.4	67.5	13.1	68.0	28.7	3.3	61.4	3.1	2.5	8.3
560				67.6	28.4	4.0	61.5	2.5	2.0	8.7
570	17.5	68.8	13.7	68.3	27.9	3.8	62.6	4.3	3.5	10.0
580				66.6	28.9	4.5	61.3	3.1	2.6	9.8
590	19.0	67.6	13.4	67.0	29.1	3.9	62.0	3.3	2.8	9.0
600				66.5	28.6	4.9	61.9	4.6	3.9	11.7
610	17.3	66.9	15.8	66.6	29.3	4.1	62.3	4.3	3.7	10.2
620				66.2	29.2	4.6	62.1	3.6	3.2	10.0
630	17.9	66.3	15.8	66.0	28.9	5.1	62.2	4.2	3.8	11.2
640				64.5	29.7	5.8	60.9	3.4	3.4	11.1
650	18.1	65.5	16.4	65.3	28.7	6.0	61.9	3.5	3.3	11.3
660				64.7	29.0	6.3	61.5	3.1	3.0	11.2
670	20.6	66.8	12.6	65.3	28.7	6.0	62.3	3.8	3.7	11.3
680				65.6	27.3	7.1	62.8	4.1	4.0	13.0
690	10.7	65.4	23.9	62.2	31.4	6.4	59.6	4.0	4.2	11.7
700				63.0	29.3	7.7	60.5	3.7	4.0	12.7
710	17.3	67.9	14.8	64.4	27.1	8.5	61.0	4.1	4.4	13.7
720				64.0	27.1	8.9	61.8	4.3	4.7	14.0
730	17.7	60.1	22.2	61.3	31.1	7.6	59.2	2.3	2.6	10.4
740				62.4	33.1	4.5	60.4	3.7	4.4	8.3
750	18.7	65.3	16.0	62.3	33.4	4.3	60.4	3.5	4.1	7.2
760				57.9	33.3	8.8	56.1	8.6	13.8	14.6
770	12.0	59.8	28.2	60.9	32.5	6.6	59.2	7.6	10.4	13.0
780				62.2	34.0	4.0	60.6	3.4	4.3	7.2
790	20.0	61.7	18.3	62.0	33.5	4.5	60.5	3.8	4.8	8.0
800				61.8	33.7	4.5	60.3	4.1	5.3	8.1
810	19.2	56.7	24.1	62.0	32.9	5.1	60.6	4.4	5.8	8.8
820				59.5	31.2	9.3	58.2	7.7	10.7	15.3
830	20.3	52.1	27.7	60.0	31.8	8.2	58.7	6.9	9.7	13.7
840				61.1	33.2	5.7	59.9	3.8	5.4	8.6
850	20.5	60.1	19.4	61.6	33.9	4.5	60.5	2.7	4.0	6.4
860				62.2	33.3	4.5	61.1	2.7	4.0	6.3
870	21.8	59.6	18.6	61.3	33.8	4.9	60.3	2.1	3.2	6.0
880				62.2	33.7	4.1	61.2	3.1	4.8	6.3
890	22.6	56.5	20.9	61.5	33.4	5.1	60.5	3.3	5.1	7.0
900				58.0	30.5	11.5	57.1	8.2	13.2	16.0
910	21.7	48.9	29.4							
930	18.8	37.8	43.4							
950	18.5	29.4	52.1							

Thus, we can conclude that the value $1 - K$ in some respect describes the quantum servival probability Λ in the process of the interaction of radiation flux with the cloud layer. In the particular case of the cloudy medium $1-K$ in the continuous spectrum was of the order of 82–88% on May 20, 1976, and on April 20, 1985 it was about 94–98%.

Note also that in cloud layers the absorption in the molecular bands becomes stronger due to the fact that photons travel a longer distances than in the free atmosphere. It can be seen in Fig. 1, where the molecular absorption in the cloud layer with $\Delta p = 160$ mbar is the same or a little bit larger than in the layer of the free atmosphere with $\Delta p = 240$ mbar.

2. WAVELENGTH DISTRIBUTION OF THE EFFECTIVE COEFFICIENTS OF REFLECTION AND TRANSMISSION OF THE RADIATION FLUX BY THE CLOUD LAYER FROM THE DATA OF OBSERVATIONS MADE ON MAY 29, 1976 AND ON APRIL 20, 1985

The effective monochromatic coefficients of reflection and transmission of the radiation flux in the above–considered observation dates calculated according to the formulas derived in Section 1, are presented in Table I and in Fig. 3. Clouds observed on May 29, 1976 were relatively thin and, as was noted above, contained strongly absorbing particles.

As a result, the albedo of the system (curve *2*) was very close to the albedo of the underlying surface (curve *3*), and they were equal to approximately 35–40%. But, as can be seen from Table I and Fig.3*a*, the effective monochromatic coefficients of reflection of the radiation flux from the clouds (curve *1*) were approximately two times less than the monochromatic albedo of the system and were equal to approximately 20%. Wavelength distribution of this coefficient was practically neutral. The wavelength distribution of the effective monochromatic coefficient of transmission of the radiation flux through the clouds (curve *4*, Fig. 3*a*) was also neutral in the visible range and was equal to approximately 65%.

Observations of the cloud layer and the atmosphere above it on April 20, 1985 made it possible to carry out a more detailed analysis of the experimental data. The cloud system in this day was more powerful than that in 1976: the effective coefficients of reflection of the radiation flux (curve *1* in Fig. 3*b*) lie within the limits 60–75% and have evidently "blue" wavelength distribution. They lie also between the values of the monochromatic albedo of the system (curve *2*) and of the underlying surface (curve *3*). The underlying surface had the spectral albedo decreasing with increase of the wavelength; the monochromatic albedo of the system had the same wavelength distribution.

The curve of the effective monochromatic coefficient of transmission of the radiation flux through the clouds lies within the limits 25–35% and increases with the wavelength (due to the reverse character of the dependence of the reflection coefficient).

The atmospheric layer within 0.2–1.7 km altitude range evidently contained not only cloud particles but also atmospheric gases which scatter the radiation in the "continuous" spectrum. This radiation scattered by the atmosphere is not simply added to the radiation scattered by cloud particles because the scattering multiplicity in clouds is quite high ($\tau \gg 1$). However, for a rough estimate of this effect let us assume that $A = A_{cl} + A_{atm}$, where A_{cl} is the part of the reflection coefficient caused by scattering on cloud particles and A_{atm} is the part of the reflection coefficient caused by scattering by atmospheric gases. We can estimate this latter part against the effective monochromatic coefficient of reflection of the radiation flux from the atmospheric layer lying above the clouds within the 1.7 km–4.5 km altitude range (indicated by points in Fig. 3*b*). Its wavelength dependence can be evidently smoothed by the dependence $A_{atm} = \alpha + \beta\lambda^{-4}$ (curve *5* in Fig. 3b). Here the second term describes the Rayleigh scattering. Taking into account the difference between the layer thicknesses and the doubling of the absorptance of the clouds in comparison with the free atmosphere made in Section 1, the estimate by the least–squares techique gives the value $\beta = 0.6$ (with λ expressed in μm). After introducing this correction in the obtained values of A, we obtain the values A_{cl} shown by curve *6* in Fig. 3*b*. This curve has practically a neutral wavelength dependence, as could be expected in the case of weakly absorbing droplets.

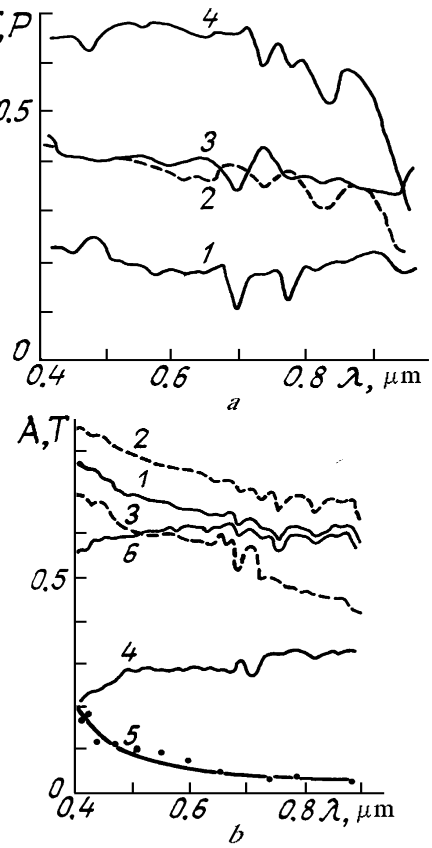

FIG. 3. Effective spectral coefficients of transmission T and reflection from the atmosphere–cloud system A, from clouds A_{cl}, from the atmosphere A_{atm}, and from the surface a. a) April 29, 1976: 1) A_{cl}, 2) A, 3) a, and 4) T; b) April 20, 1985: 1) A_{cl}, 2) A, 3) a, 4) T, 5) A_{atm}, and 6) $A = A_{cl} - A_{atm}$.

3. VERTICAL PROFILES OF RADIATION FLUXES IN CLOUDS

Vertical sounding in clouds made it possible to obtain vertical profiles of different radiative characteristics. By way of example, the vertical profiles of downwelling $F_\lambda^\downarrow$ and upwelling $F_\lambda^\uparrow$ monochromatic radiation fluxes at the wavelength $\lambda = 650$ μm are presented in Fig. 4 (the smoothed curve of the average dependence is drawn between these curves shifted along the x axis at 20 mW/cm^2·μm).

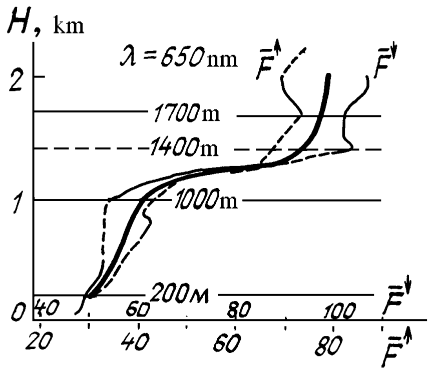

FIG. 4. Vertical profiles of downwelling $F_\lambda^\downarrow$ and *upwelling* $F_\lambda^\uparrow$ *monochromatic radiation fluxes (*λ = 650 μm*) from the observations made on April 20, 1985.*

It can be seen from Fig. 4 that the following portions can be identified in the vertical profile of $F_\lambda^\downarrow$ and $F_\lambda^\uparrow$. Upper portion about 100–200 m (1400–1600 m) in thickness, where gradual variation of the character of the vertical dependence of $F_\lambda^\downarrow$ and $F_\lambda^\uparrow$ can be seen rather than a sharp break. Evidently, the appearance of such a layer was associated with spreading of the upper cloud boundary, which was different at different sounding points. This layer is followed by the most optically active cloud layer, occupying approximately 1/4 – 1/3 of the entire thickness of cloudiness, where fluxes decrease approximately twice, while in the rest of the cloud mass they decrease only by 25–30%. Vertical profiles of radiation fluxes and other radiative characteristics will slope more steeply in the bands of the molecular absorption than in the "continuous" spectrum.

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