VERTICAL PROFILES OF SCATTERING AND ABSORPTION SPECTRAL COEFFICIENTS FOR STRATUS CLOUDS FROM AIRBORNE MEASUREMENT DATA

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We present here the formulae that relate the volume scattering and absorption coefficients of an optically thick extended and horizontally uniform layer to hemispherical fluxes of solar irradiance inside it and allow for strong vertical inhomogeneity of the layer. These formulae, and those from other studies, were applied to processing the results of spectral radiation measurements inside stratus clouds made during three airborne experiments. The spectral dependences of optical parameters of separate cloud layers were determined.

INTRODUCTION

It is well known that stratus clouds are vertically nonuniform formations. However, earlier, when determining their radiation and optical properties, these clouds were very often assumed to be uniform. Since vertical structure of stratus is of great interest when studying their physical characteristics and processes of their formation,[1] in this paper we describe the results obtained by applying the method of determining optical parameters of status from Ref. 2 to data of airborne radiation measurements at different levels inside a cloud or between the cloud layers in case of a multilayer cloudiness.

As it has been revealed in earlier studies[3] the atmospheric aerosols, including the aerosols of anthropogenic origin, are accumulated in the clouds of lower level with their distribution over clouds being dependent on the altitude. Thus, the results obtained below may be useful when investigating aerosol pollution of a cloudy atmosphere and the peculiarities of their distribution in the stratus. Stratus clouds are chosen because they differ from other types of clouds by large extension, high stability, and stronger effect they exhibit on the radiation regime of the atmosphere.[4–6] In this case the stratus may well be modeled by a plane scattering layer of large optical thickness, uniform and infinite in a horizontal plane that makes it possible to make use of analytical methods of the radiation transfer theory for interpreting the observations.

The short-wave region (0.35–0.95 μm) is considered because: 1) most of solar radiation energy concentrates in the visible range (the radiation flux at 0.4 μm wavelength several times exceeds the radiation flux at 0.9 μm wavelength); 2) in this range absorption of light in clouds is rather weak as compared to scattering and therefore it is possible to use series expansions over a small parameter when calculating asymptotic constants and functions.

We shall use exact formulae derived in Ref. 2 for such optical characteristics as single scattering albedo, ω_0, and optical thickness, τ_0, of cloud layers in our analysis of airborne measurement data on spectral solar radiation, $F^{\downarrow}$ $F^{\uparrow}$, in a cloudy atmosphere.

APPLICATION OF ASYMPTOTIC FORMULAE TO INTERPRET DATA OF AIRBORNE MEASUREMENTS

The initial data for solving the problem are the results of airborne measurements in the stratus obtained on September 24, 1972 (the solar zenith angle θ = 74°); on April 20, 1985 (θ = 49°) over the Ladozhskoe Lake (Fig. 1*a*,*c*,*d*) and on October 1, 1972 over the Kara Sea (Fig. 1*b*) (θ = 34°).[6–9] We measured spectral values of hemispherical fluxes of scattered solar radiation over a cloud, inside it at a single[8] or at several levels[6,7,9] and under the cloud cover (see Fig. 1). The conditions of the experiments were as follows:

a) the two-layer cloudiness; the measurements were carried out above the upper layer (z = 4.1 km), inside it (z = 3 km), between the cloud layers (z = 1.6 km); inside the lower layer (z = 0.6 km) and under the lower layer (z = 0.05 km)[6];

b) single-layer cloudiness; the altitude of the cloud top at 1.05 km and of the cloud bottom at 0.75 km[8];

c,d) single-layer cloudiness: altitudes of the upper and lower boundaries being at 1.4 and 0.9 km.[7,9]

The measurement spectral range in the experiments a) and b) was 0.45–0.85 μm; the number of points at the range was 41 and 17, and in the experiment c, d) the region was from 0.35 to 0.95 μm; the data presented here refer to 180 wavelengths.

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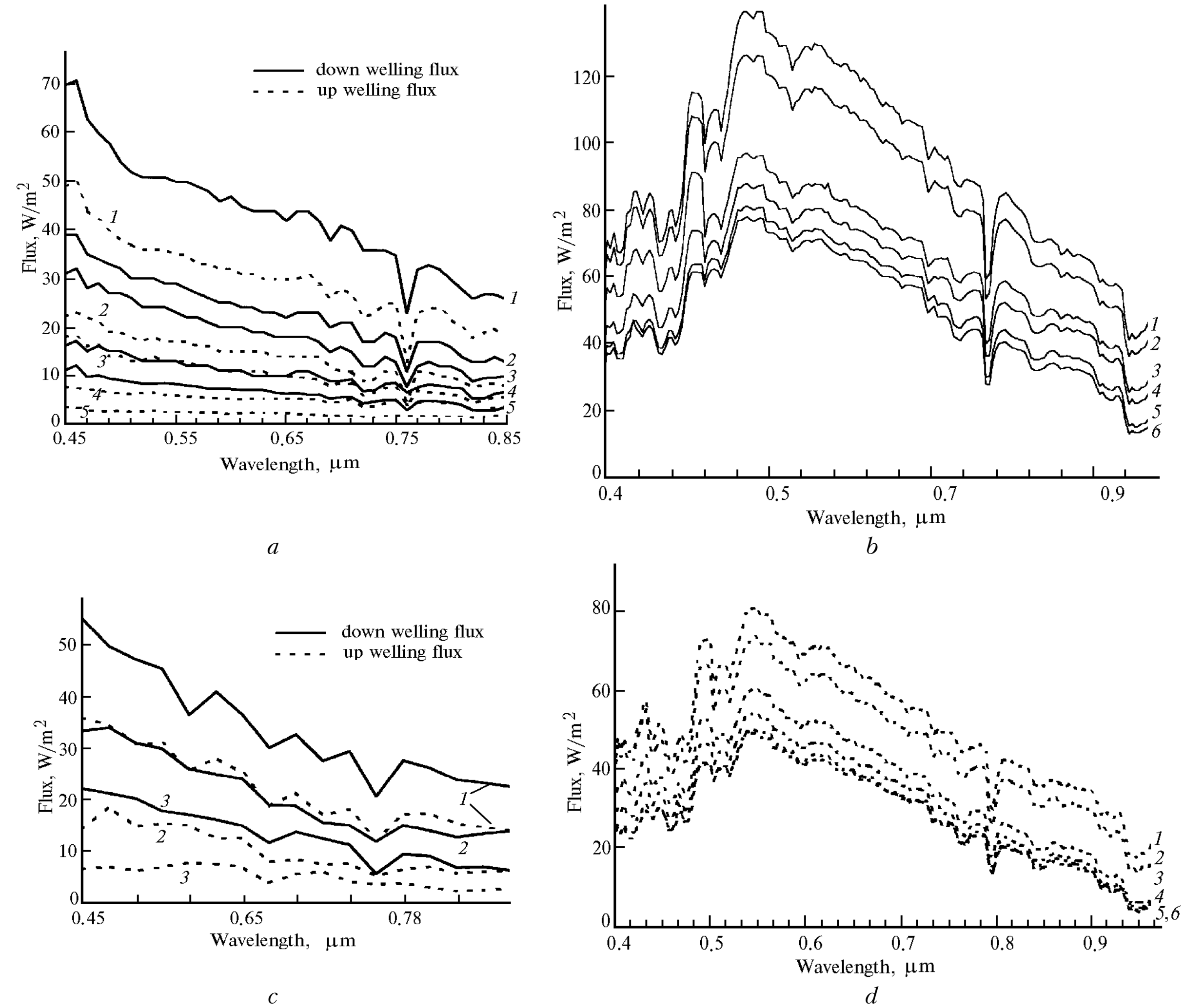

FIG. 1. Hemispherical up and down welling solar fluxes in a cloudy atmosphere according to a), b) and c) experiments, respectively. Figures at curves are the heights of measurements: a) 4.1 *(1),* 3 *(2),* 1.6 *(3),* 1.6 *(4),* 0.6 *(5),* 0.05 *(6)* km; *b)* 1.1 *(1),* 0.95 *(2),* 0.6 *(3)* km; *c, d)* 1.4 *(1),* 1.3 *(2),* 1.2 *(3),* 1.1 *(4),* 0.95 *(5),* 0.8 *(6)* km; *down welling (c) and up welling (d) fluxes.*

In the experiments that are being considered here the underlying surfaces were different:

a) the water surface (albedo $A \sim 0.20$);

b) the water surface with ice ($A \sim 0.40$);

c, d) snow and ice ($A \sim 0.65$).

The data processing has been done using formulae, expressing the values of ω_0 and τ_0 in terms of the radiation fluxes. In the experiment a) the formulae were also used that have earlier been obtained for vertically nonuniform system with two cloud layers. Taking into account the spectral values of the parameter g[10] the spectral behaviors of the cloud optical thickness were obtained for individual layers of the stratus under study. Tables I–III give the values of the single scattering albedo and optical thickness.

No difficulties occurred when using the formulae obtained in the first part[2] for processing the experimental data (a). The optical thickness between the measurement levels is rather large, and the errors related to the applicability of these formulae turned out to be less than those caused by the measurement errors. As a result, the errors of optical parameters reconstruction for the case a) are: $\Delta(1-\omega_0)/(1-\omega_0) \sim$ $\sim 6\%$, $\Delta\tau/\tau \sim 10\%$.

Note that in the experiments a) and b) (1972) the first spectrometer model was used and the data processing was performed without a computer. Therefore the measurement errors in these cases are much larger, i.e., $\Delta F^{\uparrow\downarrow}/F^{\uparrow\downarrow} \sim 5$–$6\%$ (that is seen in Fig. 1*a*,*b* as ripple on the curves) than in the experiment c) d) (1985, $\Delta F^{\uparrow\downarrow}/F^{\uparrow\downarrow} \sim 1$–$2\%$) performed on the basis of the instrument of improved modification together with the computer-based data processing. In the case of interpretation given to the results of the experiment b) the optical thickness of the layer is small, the errors of determination of optical parameters are larger ($\Delta(1-\omega_0)/(1-\omega_0) \sim 10\%$, $\Delta\tau/\tau \sim 15-20\%$) than in the cases a) and c), d) so that it was impossible to determine the optical thickness of the lower layer since the layer was too thin. In the experiment c) d), in the lower sublayer, the optical thickness was determined using the formulae that account only for light scattering. For a more correct solution of the problem in the layers of an arbitrary optical thickness some different analytical approach is needed. An approximate estimate can also be made by calculating the optical thickness of the lower sublayer as the difference between total thickness and that of the upper sublayer $\tau_2 = \tau_{Sum} - \tau_1$. The sums of thus obtained values τ_i over the altitude, namely, the optical thickness of the entire cloud layer, are denoted as Sum in Tables I–III. It was impossible to calculate the values of the quantity s^2 for the lower sublayer.

TABLE I. Single scattering albedo and optical thickness in stratus cloud obtained from airborne measurements of solar radiation fluxes on September 24, 1972.

λ, μm	z, km								
	3.55		2.30		1.10		0.33		3.55–0.33
	ω_0	τ_1	ω_0	τ_2	ω_0	τ_3	ω_0	τ_4	τ_{Sum}
0.45	0.9972	21.80	0.9912	38.00	0.9947	28.52	0.9961	3.88	92.20
0.46	0.9968	18.48	0.9953	39.91	0.9945	27.00	0.9950	3.25	88.64
0.47	0.9956	20.93	0.9979	46.74	0.9943	28.20	0.9953	4.22	100.09
0.48	0.9959	23.12	1.0000	43.65	0.9939	27.91	0.9930	3.74	98.42
0.49	0.9966	18.87	0.9972	41.09	0.9827	27.69	0.9914	3.34	90.99
0.50	0.9973	23.47	1.0000	43.49	0.9932	31.17	0.9903	2.96	101.09
0.51	0.9974	22.01	1.0000	42.72	0.9913	27.24	0.9821	3.63	95.60
0.52	0.9971	21.01	0.9952	40.49	0.9951	33.45	0.9951	4.67	96.62
0.53	0.9971	20.74	0.9950	39.47	0.9950	32.60	0.9950	4.55	97.36
0.54	0.9972	18.03	0.9967	41.79	0.9931	30.95	0.9945	4.20	94.97
0.55	0.9970	20.75	0.9948	38.10	0.9949	32.12	0.9927	3.67	94.64
0.56	0.9964	21.68	0.9952	39.50	0.9957	32.95	0.9949	4.08	98.21
0.57	0.9951	17.19	0.9968	41.87	0.9936	29.81	0.9931	3.69	92.56
0.58	0.9955	18.46	0.9971	42.52	0.9953	28.46	0.9923	3.73	93.17
0.59	0.9962	18.28	0.9969	43.38	0.9934	26.87	0.9963	4.59	93.12
0.60	0.9954	17.58	0.9969	43.11	0.9934	26.70	0.9963	4.56	91.95
0.61	0.9954	20.28	0.9975	43.77	0.9937	25.30	0.9938	3.97	93.37
0.62	0.9963	19.92	0.9973	45.79	0.9943	19.82	1.0000	5.12	90.65
0.63	0.9947	23.81	1.0000	44.42	0.9944	25.56	0.9993	5.31	99.10
0.64	0.9954	18.35	0.9971	47.69	0.9930	28.16	0.9972	5.37	99.57
0.65	0.9964	25.12	0.9970	44.14	0.9925	29.05	0.9959	5.22	103.53
0.66	0.9952	18.61	0.9973	43.50	0.9938	31.32	0.9929	4.10	97.52
0.67	0.9964	22.02	0.9984	51.40	0.9921	29.34	0.9921	4.04	106.78
0.68	0.9957	16.85	0.9968	43.85	0.9924	27.07	0.9962	5.40	93.17
0.69	0.9952	17.10	0.9970	41.00	0.9912	25.67	0.9934	4.24	88.01
0.70	0.9964	21.76	0.9891	37.72	0.9898	22.77	0.9960	4.97	87.22
0.71	0.9961	22.32	0.9882	38.51	0.9912	24.00	0.9977	6.25	91.08
0.72	0.9915	17.13	0.9916	39.81	0.9882	22.97	0.9949	4.50	84.41
0.73	0.9933	18.64	0.9913	40.60	0.9913	23.09	0.9989	5.04	87.37
0.74	0.9962	17.42	0.9949	37.12	0.9907	24.86	0.9962	5.54	84.94
0.75	0.9966	18.39	0.9956	44.32	0.9919	25.51	0.9989	7.46	95.68
0.76	0.9808	20.32	0.9740	46.72	0.9600	23.68	0.9972	7.64	98.32
0.77	0.9964	19.64	0.9974	45.24	0.9928	25.03	0.9993	7.46	97.37
0.78	0.9968	19.84	0.9964	45.19	0.9866	22.54	0.9984	7.59	95.12
0.79	0.9988	20.73	0.9953	41.71	0.9899	26.23	0.9972	6.63	95.30
0.80	0.9974	20.91	0.9996	46.53	0.9863	23.89	0.9965	6.24	97.56
0.81	0.9962	16.86	0.9980	44.58	0.9841	29.81	0.9948	5.49	96.65
0.82	0.9958	17.75	0.9969	46.05	0.9875	26.93	0.9944	4.31	95.04
0.83	0.9959	19.45	0.9995	45.43	0.9882	27.07	0.9950	4.60	96.55
0.84	0.9978	18.06	0.9956	42.04	0.9936	30.95	0.9940	3.52	94.57
0.85	0.9954	17.42	0.9969	45.40	0.9918	33.85	0.9931	1.93	98.60

TABLE II. Single scattering albedo and optical thickness in stratus cloud obtained from airborne measurements of solar radiation fluxes on October 1, 1972.

λ, μm	*z*, km				
	1.0		0.8		Whole layer 1.05–0.75
	ω_0	τ_1	ω_0	τ_2	τ_{Sum}
0.45	0.9986	4.5	0.9874	1.7	6.2
0.48	–	3.8	0.9980	1.6	5.4
0.50	–	4.4	0.9935	1.5	5.9
0.53	–	3.5	0.9912	0.5	4.0
0.58	–	4.0	0.9967	0.4	4.4
0.60	0.9877	3.7	0.9855	0.1	3.8
0.65	–	3.2	0.9879	–	3.1
0.69	0.9218	3.5	0.9786	–	3.2
0.70	0.9792	3.7	0.9794	–	3.5
0.72	0.8636	–	0.9747	–	3.9
0.75	0.9251	1.5	0.9968	0.7	2.2
0.76	0.8189	–	0.9693	–	3.1
0.78	0.9582	3.6	0.9745	0.5	4.1
0.80	0.9667	3.2	0.9873	0.6	3.8
0.82	0.9811	2.0	0.9814	0.5	2.5
0.83	0.9584	–	0.9801	–	2.0
0.85	0.9218	–	0.9879	–	2.1

Taking into account the magnitudes of s^2 and τ' as well as the distances between the levels for which the measurements of radiation fluxes and spectral dependences of the scattering phase function parameter g[10] had been carried out we determined the values of the volume absorption and scattering coefficients for cloud layers between the measurement levels that are presented in Figs. 2 and 3.

The errors of reconstruction of the values of optical parameters varied with the increase of wavelength since they depend on the absorption value. The estimate of the errors averaged over the spectrum gave 6–10% for ω_0 and 15% for τ, σ and k. The errors are larger in the UV region because they increase due to larger instrumental errors. In the experiments a) and b) they are also larger because of a less perfect model of the spectrometer used. The error values also increase with the absorption growth because at strong absorption the accuracy of the asymptotics used decreases. The ripple on curves was caused by the measurement errors in the radiation fluxes as is seen from the experiment c) carried out with the use of a more precise instrumentation. It is seen that the curves $\sigma(\lambda)$ and $k(\lambda)$ are more smooth.

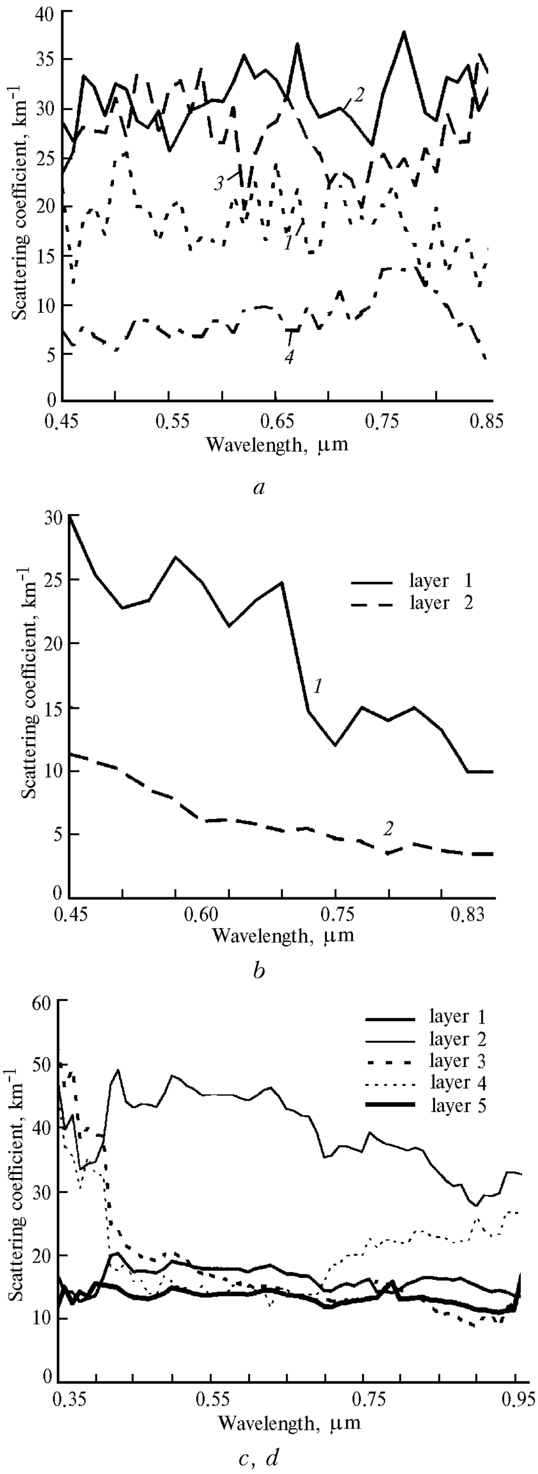

FIG. 2. Spectral values of the volume scattering coefficient in layers inside of cloud between the measurement levels. a, b, c, and d correspond to a), b), c), and d) experiments. Figures at curves point out a number of the layer: a: 4.1–3 *(1),* 3–1.6 *(2),* 1.6–0.6 *(3),* 0.6 –0.05 *(4)* km *layer; b:* 1.1–0.95 *(1),* 0.95–0.6 *(2)* km *layer; c and d:* 1.4–1.3 *(1),* 1.3–1.2 *(2),* 1.2–1.1 *(3),* 1.1–0.95 *(4), and* 0.95–0.8 *(5)* km.

TABLE III. Single scattering albedo and optical thickness in stratus cloud obtained from airborne measurements of solar radiation fluxes on April 20, 1985.

λ, μm	z, km										
	1.35		1.25		1.15		1.05		0.87		1.4–0.8
	ω_0	τ_1	ω_0	τ_2	ω_0	τ_3	ω_0	τ_4	ω_0	τ_5	τ_{Sum}
0.35	0.9831	1.75	0.9968	4.86	0.9949	5.32	0.9974	4.61	–	1.75	18.30
0.36	0.9891	1.45	0.9996	3.98	0.9942	4.67	0.9964	3.78	–	3.75	17.63
0.37	0.9876	1.45	0.9991	4.21	0.9944	4.95	0.9971	3.58	–	1.87	16.05
0.38	0.9971	1.28	0.9966	3.36	0.9899	3.87	0.9937	3.08	–	2.15	13.74
0.39	0.9925	1.33	0.9949	3.46	0.9881	4.03	0.9936	3.56	–	1.28	13.66
0.40	0.9961	1.37	0.9962	3.48	0.9906	3.94	0.9934	3.33	–	2.35	14.47
0.41	0.9977	1.66	0.9976	3.78	0.9920	3.90	0.9944	3.26	–	2.31	14.91
0.43	0.9920	2.06	0.9937	4.95	0.9957	2.39	0.9973	1.77	–	2.25	13.41
0.45	0.9889	1.77	0.9918	4.36	0.9956	2.09	0.9967	1.66	–	2.01	11.89
0.47	0.9876	1.77	0.9916	4.41	0.9960	1.98	0.9974	1.48	–	1.98	11.62
0.49	0.9867	1.83	0.9914	4.58	0.9959	2.02	0.9962	1.69	–	2.11	12.23
0.50	0.9876	1.93	0.9918	4.90	0.9964	2.07	0.9971	1.63	–	2.26	12.74
0.51	0.9873	1.91	0.9917	4.82	0.9960	1.99	0.9966	1.59	–	2.21	12.52
0.53	0.9859	1.85	0.9910	4.66	0.9963	1.79	0.9973	1.38	–	2.10	11.77
0.55	0.9857	1.82	0.9908	4.57	0.9961	1.72	0.9965	1.40	–	2.08	11.60
0.57	0.9858	1.83	0.9906	4.57	0.9961	1.65	0.9954	1.50	–	2.10	11.65
0.59	0.9854	1.81	0.9904	4.52	0.9960	1.56	0.9939	1.62	–	2.10	11.62
0.60	0.9842	1.77	0.9898	4.43	0.9960	1.55	0.9945	1.50	–	2.09	11.35
0.61	0.9850	1.83	0.9904	4.55	0.9961	1.50	0.9943	1.48	–	2.12	11.49
0.63	0.9858	1.89	0.9909	4.69	0.9962	1.54	0.9939	1.59	–	2.21	11.91
0.65	0.9852	1.76	0.9903	4.36	0.9956	1.42	0.9928	1.53	–	2.10	11.16
0.67	0.9839	1.72	0.9903	4.25	0.9950	1.36	0.9919	1.51	–	2.06	10.91
0.69	0.9825	1.62	0.9895	4.01	0.9944	1.32	0.9908	1.44	–	1.93	10.31
0.70	0.9804	1.50	0.9903	3.74	0.9920	1.36	0.9865	1.59	–	1.82	10.01
0.71	0.9829	1.49	0.9912	3.62	0.9920	1.31	0.9849	1.88	–	1.85	10.14
0.73	0.9866	1.60	0.9918	3.76	0.9913	1.32	0.9819	2.13	–	1.92	10.73
0.75	0.9874	1.63	0.9935	3.66	0.9933	1.31	0.9849	2.05	–	1.97	10.62
0.77	0.9822	1.48	0.9913	3.88	0.9895	1.63	0.9830	2.18	–	2.02	11.19
0.79	0.9870	1.46	0.9926	3.78	0.9884	1.60	0.9815	2.30	–	2.02	11.16
0.80	0.9879	1.53	0.9934	3.71	0.9898	1.50	0.9808	2.27	–	2.00	10.96
0.81	0.9889	1.60	0.9943	3.68	0.9899	1.34	0.9795	2.28	–	2.01	10.91
0.83	0.9897	1.69	0.9952	3.68	0.9903	1.35	0.9777	2.47	–	2.04	11.24
0.85	0.9871	1.68	0.9963	3.36	0.9944	1.13	0.9790	2.38	–	1.96	10.05
0.87	0.9902	1.66	0.9982	3.12	0.9927	1.14	0.9774	2.28	–	1.92	10.12
0.89	0.9894	1.63	0.9993	2.90	0.9923	1.00	0.9720	2.34	–	1.83	9.70
0.90	0.9875	1.58	0.9968	2.71	0.9890	1.01	–	2.63	–	1.76	9.66
0.91	0.9899	1.52	0.9979	2.98	0.9836	1.06	–	2.44	–	1.74	9.74
0.93	0.9874	1.51	0.9962	3.01	0.9838	0.97	–	2.37	–	1.69	9.52
0.95	0.9826	1.42	0.9903	3.37	0.9737	1.32	–	2.71	–	1.75	10.57
0.96	0.9873	1.40	0.9917	3.30	–	1.32	–	2.60	–	1.75	10.45

DISCUSSION OF THE RESULTS

The values of single scattering albedo attract more attention (see Tables I–III). Note that in all cases of the radiation experiment data interpretation (for example, Ref. 11) the values of single scattering albedo are much less than those obtained from the calculations by the Mie theory based on the commonly accepted microphysical models. We think that this fact is an evidence, at a level of an elementary volume, of the effect of "excess" ("anomalous") absorption of short-wave radiation in a cloud, that is being widely discussed in the literature. It seems likely that the volume element, which is normally taken in the models for calculation of radiation characteristics based on the radiation transfer theory and averages the parameters of three principal cloud components (molecules, aerosol outside the droplets and cloud droplets), is too large. Therefore the averaging occurs at the initial stage of solving the physical problem, but not at its final stage. This fact leads to an incorrect result, namely, calculated value underestimates the radiation absorption that contradicts the data of observations. It is just this underestimation that makes the effect of "excess" absorption in clouds. On the whole the spectral behavior of the value ω_0 in the spectral range considered is identical to the dependences obtained earlier.[11]

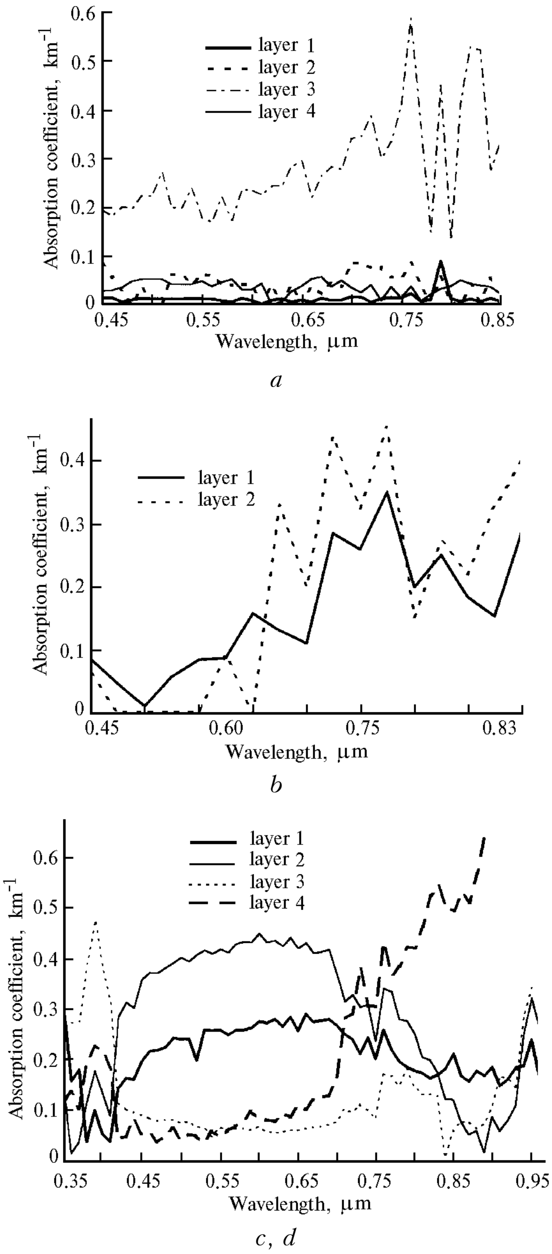

FIG. 3. Spectral values of the volume absorption coefficient in layer inside of cloud between the measurement layers. a, b, c, and d correspond a), b), c), and d) experiments. Figures at curves are the same as in Fig. 2.

The optical thickness of an individual sublayer does not show any clear spectral dependence against the background of variations due to the errors of the method used. However, the integrated values of optical thickness decrease with increasing wavelength, as was noted earlier when interpreting the data of other observations.[11]

Spectral dependences of the volume scattering coefficient presented in Figs. 2*a*,*b*, and *c* show a considerable vertical inhomogeneity of the stratus. The scattering coefficient in the upper cloud layers exceeds, in both cases, the scattering coefficient of the lower layers. The volume scattering coefficient of the cloud, as a whole, determined earlier on the basis of measurements of radiation fluxes at the cloud boundaries,[11] coincides, accurate to the experimental error, with the values of σ obtained in these experiments and averaged over the entire layer.

The volume absorption coefficient of individual cloud layers also reveals a strong vertical inhomogeneity of the cloud. In the spectral dependences $k(\lambda)$ for the upper cloud layers in the experiments b), c) d) the influence of the Shappouis absorption band of ozone (0.65 μm) is seen, in addition to the absorption bands of oxygen and water vapor (0.68; 0.72; 0.76 μm, etc.), while in the curves for lower parts of clouds no such an effect is observed. The absorption coefficient is larger for lower layers of a cloud in cases b), c), and d) that might be indicative of the preferred accumulation of the atmospheric aerosols in the lower cloud layer.

In the experiment c) the absorption coefficient of the lower part of the cloud layer (1.1–1.0 km) monotonically increases with increasing wavelength that has explicitly seen before[11] when considering the cloud layer as a whole and being typical for the products of organic fuel combustion.

CONCLUSION

It should be noted that earlier, in Ref. 12, the problem was solved on determining optical parameters at one level inside a cloud assuming only light scattering to occur there and based on the measurements with a filter spectrometer at 15 wavelengths (in our case the measurement data used have been carried out in the spectral range of 0.35–0.95 μm). When theoretically analyzing possible applications of radiation measurements[13] the method was proposed and corresponding analytical apparatus developed based on the ratio of intensities or fluxes of scattered solar radiation measured at different levels inside a cloud layer. Unfortunately, no results obtained using this method in application to measurement data processing are known.

The above analytical expressions are a good basis for the interpretation of the airborne radiation measurement data and for reconstructing vertical profiles of the optical parameters of stratus from this data. In spite of considerable errors in reconstructed values of ω_0 and especially τ, the realistic values and spectral dependences of the values sought were obtained. Note that at higher measurement accuracy (a more advanced model of the instrument in the experiments of 1985) the precision of the results becomes acceptable for solving the problems of atmospheric optics. It is evident that, on the whole, the results of solving of inverse problem considered reveal some common properties of the structure and composition of stratus under different experimental conditions. Undoubtedly, when taking into account the climate forming role of clouds in numerical modeling of the climate it is important to take into consideration the short-wave radiation absorption by clouds.

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