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RESEARCH TRANSLATION

**The Thickness and Radiation Characteristics  
of St and Sc Clouds as Determined  
by the Intensity of Total Radiation  
at the Surface of the Earth**

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THE THICKNESS AND RADIATION CHARACTERISTICS  
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Translation of

Opredelenie moshchnosti i nekotorykh radiatsionnykh kharakteristik  
sloistykh i sloisto-kuchevykh oblakov po intensivnosti  
summarnoy radiatsii u poverkhnosti Zemli

by

N. I. Gořsa and T. V. Zhelezniakova

Kiev. Ukrainskiĭ Nauchno-Issledovatel'skiĭ Gidrometeorologicheskiĭ  
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**THE THICKNESS AND RADIATION CHARACTERISTICS  
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The relation between the intensity of total radiation at the surface of the earth and the thickness of St and Sc clouds is investigated. Nomograms are plotted which permit the thickness of St and Sc layers to be determined with adequate accuracy. The nomograms are used to compute the coefficients of the total extinction of radiation by clouds and to derive the relationship of these coefficients with the altitude of the sun and the thickness of the cloud layer.

Thickness is one of the important parameters of a cloud layer. Data on cloud thickness are required to solve a number of practical and scientific problems, e. g., to determine the stored water in a cloud layer or the position of a cloud top, to solve problems related to the forecasting of the evolution of clouds, etc. Despite this, determination of this parameter is restricted at present to aircraft and balloon soundings. These methods are costly, are used in a small number of stations, and are limited in time to a few soundings a day. Also, they are not devoid of important deficiencies which will be mentioned below. As a result, the workers in the hydrometeorological service are often unable to obtain even an approximate estimate of the thickness of the cloud layer.

Meanwhile, theoretical [8] and experimental [7, 12, 14] research has shown that it is possible in principle to determine this parameter by ground-level actinometric measurements.

We know that the intensity of radiation fluxes at the surface of the earth is determined to a significant degree by the nature of the cloud cover and primarily by the total moisture content and thickness of the cloud layer. This circumstance permitted E. P. Novosel'tsev [9] to develop a simple method for tentatively evaluating the liquid-water content of high clouds by using ground-level measurements of the intensity of direct solar radiation. The propositions discussed in [9] served as the basis for developing an empirical method of determining the thickness of low clouds from the intensity of the total radiation at the surface of the earth. Of all the types of low clouds, we selected the simplest types (as regards their effect on the total radiation), i. e., St and Sc.

Let  $Q_t$  and  $Q_b$  designate the total radiation intensities at the top and base of the cloud layer. Then the ratio  $Q_b/Q_t$  will produce the curve of the total radiation transmitted by the cloud. The value of this ratio is determined by the global radiation reflected from the cloud top and the global radiation absorbed by the cloud layer. It was shown in [7, 8, 14, 15], that the reflection and absorption of radiation by clouds depends on a great number of factors, the most important of these being the thickness and the total moisture content. The data available to us from aircraft soundings gives information only on the thickness of clouds. The moisture content could not be determined because data on the liquid-water content was lacking. The papers referred to above indicate that an increase in cloud thickness is accompanied by an increase in the albedo, and by an increase in the absorption of global radiation, and thus,

by a decrease in  $Q_b/Q_t$ . As a result, the value of the ratio  $Q_b/Q_t$  may be used to determine the thickness of a cloud layer. However determination of the quantities  $Q_b$  and  $Q_t$  requires aircraft or balloon ascents, during which the cloud thickness can be determined directly. Therefore, one must establish to what extent the quantities  $Q_t$  and  $Q_b$  are related to the intensity of global radiation at the earth's surface.

To solve this problem, we will assume, as did N. I. Chel'tsov [14] and E. P. Novosel'tsev [9], that when there are no other clouds above a given cloud layer, the quantity  $Q_t$  is proportional to  $Q_0$ , i. e., the intensity of global radiation at the earth's surface when the sky is clear.

$$Q_t = \frac{1}{k_1} Q_0,$$

where coefficient  $k_1$  characterizes the transmission of global radiation by a layer of air extending from the top of the cloud layer to the surface of the earth.

Similarly

$$Q_b = \frac{1}{k_2} Q_s,$$

where  $Q_s$  is the intensity of global radiation at the surface of the earth when there is a solid St or Sc cloud cover and  $k_2$  is the coefficient that characterizes the transmission of global radiation by the layer below the cloud.

We can formulate an equation that shows the relationship between the ratio  $Q_b/Q_t$  and the data of measurements at the surface of the earth

$$\frac{Q_b}{Q_t} = \frac{k_1 Q_s}{k_2 Q_0}. \quad (1)$$

From formula (1), it follows that the use of ground-level actinometric measurements to characterize the transmission of global radiation by clouds depends on the difference between coefficients  $k_1$  and  $k_2$ . This difference results from the fact that  $k_1$  and  $k_2$  pertain to layers of air with different thicknesses.

By using the data of experimental measurements of absorption in the free atmosphere [1, 5], one can determine the ratio  $k_1/k_2$  for average and extreme conditions that occur when there are St and Sc clouds.

From the data of soundings that were used, it follows that under average conditions, the bases of the St and Sc may be roughly taken to equal 500 m and their thickness also can be taken to be 500 m (Table 1). On the basis of the data for Kiev in [1], we find that when the altitude of the sun is  $43^\circ$ , about  $0.036 \text{ cal/cm}^2 \text{ min}$  is absorbed in the 0-500 m layer of the atmosphere, while  $0.054 \text{ cal/cm}^2 \text{ min}$  is absorbed in the 0-1000 m layer. The intensity of global radiation,  $Q$ , at the earth's surface can be determined from the data in [2]. From this work, it follows that  $Q_\odot = 1.100 \text{ cal/cm}^2 \text{ min}$  for  $h_\odot = 43^\circ$ . Then, when the sky is clear, the intensity of global radiation at levels corresponding to the average heights of the tops and bases of St and Sc will equal:  $Q_{\odot t} = 1.154 \text{ cal/cm}^2 \text{ min}$  and  $Q_{\odot b} = 1.136 \text{ cal/cm}^2 \text{ min}$ . On the basis of these data, we find that  $k_1/k_2 = 0.983$ .

For extreme conditions, the height of the bases of St and Sc can be taken to equal 1500 m and the thickness can also be taken to equal 1500 m (Table 1). In this case, when the altitude of the sun is  $43^\circ$ , absorption in the 0-1500 m layer is about  $0.075 \text{ cal/cm}^2 \text{ min}$  and in the

Table 1

The Frequency of St and Sc with Different Thicknesses,  
Kiev, 1954-1962

		Thickness, m												
		100-200	210-300	310-400	410-500	510-600	610-700	710-800	810-900	910-1000	1010-1100	1110-1200	1210-1300	1310-1400
St														
No. of cases		11	11	10	11	10	10	10	4	3	3	2	1	2
Frequency, %		12,5	12,5	11,4	12,5	11,4	11,4	11,4	4,5	3,4	3,4	2,3	1,2	2,2
Sc														
No. of cases		19	25	31	32	18	18	7	6	5	2	1	1	-
Frequency, %		11,5	15,2	18,8	19,4	10,9	10,9	4,3	3,6	3,0	1,2	0,6	0,6	-

0-3000 m layer the absorption is about  $0.122 \text{ cal/cm}^2 \text{ min}$ . If we make a computation similar to the previous one, we obtain  $k_1/k_2 = 0.963$ .

The results given indicate that the difference between  $k_1$  and  $k_2$  is not great (less than 4%) even under the most unfavorable conditions. Therefore, it can be assumed that

$$\frac{Q_b}{Q_t} \approx \frac{Q_s}{Q_0} \quad (2)$$

represents an adequate approximation. Thus, the ratio  $Q_s/Q_0$  reliably characterizes the transmission of global radiation. Furthermore, the aforementioned confirms the conclusions in [9, 14] regarding the possibility of neglecting the effects of the subcloud layer on the attenuation of short-wave radiation by clouds.

To obtain the relationship between the thickness,  $H$ , of St and Sc and the intensity of global radiation at the surface of the earth,  $Q_g$ , we used the aircraft sounding data from the Kiev Air Weather Station and actinometric measurements made at the experimental station of the Ukrainian Hydrometeorological Research Institute (Bagrinova Gora, Kiev) during the period from 1954 to 1962. We selected cases where the amount and type of cloud cover was the same at both stations (the distance between them is about 5 km) and the sky was clear above the St or Sc clouds or the middle (high) clouds did not exceed three-tenths. Of all the cases where the cloud cover had a multilayer structure, we selected only those that had two Sc layers or a combination of St and Sc. Here, the thickness of the cloud layer was taken to be the sum of the thicknesses of both layers. As a total for the nine year period, we selected 165 cases with Sc and 88 cases with St.

Tables 1 and 2 give the frequency of clouds with different thicknesses and different albedo values at their tops for all the cases examined. The data in these Tables give us an idea of the variation in the thickness of St and Sc and of their reflective properties which are closely related to the thickness of the cloud layer.

**Table 2**

**Frequency of the Albedo Values of the Tops of St and Sc.  
Kiev, 1954-1962**

		Albedo range, %										
		31-35	36-40	41-45	46-50	51-55	56-60	61-65	66-70	71-75	76-80	81-85
		<b>St</b>										
No. of cases		1	2	4	6	8	12	6	17	15	17	--
Frequency, %		1,1	2,3	4,5	6,8	9,1	13,6	6,8	19,4	17,1	19,3	--
		<b>Sc</b>										
No. of cases		--	2	4	6	8	9	19	17	23	27	50
Frequency, %		--	1,2	2,4	3,6	4,8	5,5	11,6	10,4	13,9	16,3	30,3

The determination of the function  $Q_{\odot} = f(H)$  is complicated by the fact that other factors besides the thickness of the cloud layer, primarily the altitude of the sun  $h_{\odot}$ , the albedo of the earth's surface, and the albedo of the cloud base, have a substantial effect on the quantity  $Q_s$ .

To allow for the effect of the altitude of the sun, N. I. Chel'tsov [14] proposed the use of the ratio  $Q_s/Q_{\odot}$  instead of  $Q_s$ . According to Chel'tsov, the relationship of  $Q_s/Q_{\odot}$  with  $h_{\odot}$  is secondary. In order to verify his assertion, we plotted  $Q_s/Q_{\odot}$  as a function of  $H$  for different altitudes of the sun. We found that although the dependence of  $Q_s/Q_{\odot}$  on  $h_{\odot}$  is considerably less than the same dependence for  $Q_s$ , it is still important. For example, when the clouds are 500 m thick, a change in  $h_{\odot}$  from  $10^{\circ}$  to  $30^{\circ}$  leads to an increase in the ratio  $Q_s/Q_{\odot}$  from 0.14 to 0.21. The reasons for this relationship will be examined below.

It is clear from the foregoing that the ratio  $Q_s/Q_{\odot}$  does not make sufficient allowance for the effect of  $h_{\odot}$ . In our work, allowance for the effect of  $h_{\odot}$  on the function  $Q_s/Q_{\odot} = f(H)$  was achieved by plotting a family of curves, each of which corresponded to a specific altitude of the sun.

The increase in the scattered radiation  $\Delta D$  caused by  $r$  multiple reflections of the radiation from the surface of the earth and the base of the clouds was computed by a formula taken from [6]

$$\Delta D = D_0 \frac{A_e A_{cl}}{1 - A_e A_{cl}}, \quad (3)$$

where  $D_0$  is the intensity of scattering of the radiation which corresponds to a zero albedo of the earth's surface ( $A_e = 0$ ) and  $A_{cl}$  is the albedo of the base of the cloud cover.

When the sky is cloudy,  $D$  equals  $Q_s$ . Therefore, we will use only the term "global radiation" from now on. Using formula (3), it is easy to derive the expression for reducing the intensity of global radiation, measured for a given albedo value of the earth's surface  $A_e$  (henceforth written as  $Q_{s,a}$ ), to the intensity  $Q_{s,0}$  which corresponds to zero albedo ( $A_e = 0$ )

$$Q_{s,0} = Q_{s,a} (1 - A_e A_{cl}). \quad (4)$$

Values of  $A_e$  were determined for each case either from the data of recordings of radiation reflected from the surface of the earth or from the data of aircraft soundings closest in time to the actinometric observations. The albedo of the base of the cloud layer was assumed to equal the albedo of the top and was determined from the data of Chel'tsov with allowance for the type and thickness of the clouds. Table 3 gives the values of  $A_{cl}$  for St and Sc with different thicknesses. It should be noted that Chel'tsov's data on the albedo of the cloud cover, as well as data of other authors [7, 15], were given without indicating the altitudes of the sun at which the measurements were made. Meanwhile, there is justification for assuming that  $A_{cl}$  must determinately depend on  $h_{\odot}$ . This is particularly indicated by the marked anisotropy in the zonal distribution of radiation reflected from the tops of St [3] and by the theoretical research of E. M. Feigel'son [11]. The assumption that the albedos of the top and base of the clouds are equal is also subject to verification, since the top and the base substantially differ in structure and in their illumination conditions.

The possible difference between the albedos at the top and base of a cloud layer can be determined from the following considerations.

Usually, the albedo at the top of clouds is defined as the ratio

$$A_{cl} = \frac{R_t}{Q_t}$$

where  $R_t$  is the ascending stream of radiation at the level of the cloud top.

Table 3

The Mean Values of the Measured Albedos (from the Data of N. I. Chel'tsov) and the True Albedos of St and Sc as a Function of Their Thickness

Albedo	Thickness of cloud layer, m									
	100	150	200	250	300	400	500	600	700	>800
Measured for St	0.35	0.41	0.47	0.52	0.56	0.62	0.67	0.72	0.74	0.76
Measured for Sc	0.37	0.45	0.53	0.60	0.65	0.71	0.80	0.82	—	—
True for St	0.26	—	0.42	—	0.54	0.61	0.66	0.72	0.74	0.76
True for Sc	0.31	—	0.50	—	0.64	0.73	0.79	0.82	—	—

This stream of radiation is made up of two parts. One part is the radiation reflected and back-scattered by the clouds ( $R_t'$ ) and the other is that part of the radiation reflected by the surface of the earth which penetrates through the cloud layer ( $\delta R_e$ ),

$$R_t = R_t' + \delta R_e. \tag{5}$$

Then

$$A_{cl} = \frac{R_t'}{Q_t} + \frac{\delta R_e}{Q_t}. \tag{6}$$

The quantity  $\delta R_e$  depends on the albedo of the earth's surface,  $A_e$ , and, therefore, the measured value of  $A_{cl}$  also depends on  $A_e$  to a certain extent. This dependence has been well traced in A. P. Koptev's

data [7] on measurements of  $A_{cl}$  above snow-covered ice and water. The first term in Eq. (6) does not depend on  $A_e$ . This term properly characterizes the reflective properties of the top of the cloud cover, except for the part of the radiation incident on the cloud base that is transmitted by the cloud. Therefore, this can be called the true albedo of the cloud,  $A'_{cl}$ . The difference between the true and the measured albedos of the cloud top will be less as  $A_e$  becomes smaller and when  $A_e = 0$ , they equal each other. On the basis of formula (6), we obtain the following expression for  $A'_{cl}$ :

$$A'_{cl} = A_{cl} - \frac{\delta R_e}{Q_t}. \quad (7)$$

The radiation conditions are somewhat different for the base of the cloud layer than for the top.

In the first place, the base, in contrast to the top, is exposed only to diffuse radiation (there is no direct solar radiation). However, since the dependence of a cloud's albedo on the angle of incidence of the radiation has not yet been experimentally studied, we cannot determine the contribution that this factor makes to the difference in the albedos at the base and top of a cloud.

Secondly, if there are no other clouds above the cloud layer, the radiation stream reflected by the base has practically no part analogous to  $\delta R_e$  in  $R_t$ . Therefore, in a certain sense, the radiation conditions of the base are close to those that would hold at the top if  $A_e = 0$ . Whence, it follows that in the first approximation, the albedo of the base of the cloud layer can be assumed to equal  $A'_{cl}$ . To determine the latter, one must find  $\delta R_e$ .

On the basis of the Bouguer-Lambert law, let us find the expression for  $\delta R_e$ , viz.,

$$\delta R_e = \Delta E e^{-k_a l}, \quad (8)$$

where  $k_a$  is the absorption coefficient in  $m^{-1}$  for short-wave radiation in clouds and

$$\Delta E = E^\uparrow - E^\downarrow, \quad (9)$$

where  $E^\uparrow$  and  $E^\downarrow$  are the radiation streams incident on the base and reflected from it.

If we neglect the effect of the layer beneath the clouds, we can assume that the radiation stream emerging from the cloud toward the earth's surface equals  $Q_{s,0}$  (the measured amount of global radiation  $Q_{s,a}$  also includes the increase in radiation due to secondary reflections). If one makes allowance for the multiple reflections of the radiation between the surface of the earth and the base of the clouds, it is easy to obtain expressions for  $E^\uparrow$  and  $E^\downarrow$ :

$$E^\uparrow = Q_{s,0} A_e (1 + A_e A'_{cl} + A_e^2 A'^2_{cl} + \dots), \quad (10)$$

$$E^\downarrow = Q_{s,0} A_e A'_{cl} (1 + A_e A'_{cl} + A_e^2 A'^2_{cl} + \dots). \quad (11)$$

On the basis of Eqs. (7)-(11), neglecting terms of the second order or higher, we obtain the formula for determining  $A'_{cl}$

$$A'_{cl} = \frac{A_{cl} - \frac{Q_{s,0}}{Q_t} A_e e^{-k_a l}}{1 - \frac{Q_{s,0}}{Q_t} A_e (1 - A_e) e^{-k_a l}}. \quad (12)$$

For a tentative evaluation of  $A'_{cl}$ , we use the following data. The quantities  $A_{cl}$  for St and Sc of different thicknesses are taken from [14], where they were obtained at the average albedo value of the earth, viz.,  $A_e = 0.17$ . The quantity  $Q_t$  can be determined from the relationship,  $Q_t = 1.065Q_\odot$ , obtained in the same paper. The quantity  $k_a$  can be determined on the basis of the data in [7]. On the average,  $k_a = 1.1 \times 10^{-3} \text{ m}^{-1}$  can be taken for St and Sc. The magnitudes of the true albedo of the cloud layer are computed in this manner for  $h_\odot = 20^\circ$  and presented in Table 3 along with the data of Chel'tsov. A comparison of these data show that the differences between the measured and true albedo values of the cloud cover (and, consequently, the differences between the albedos of the top and base of the clouds) are substantial when the clouds are thin (100-200 m). In such cases, the true albedo is 0.05-0.09 less than the measured albedo. When the clouds are more than 400 m thick, both magnitudes are practically equal.

It is very important to calculate the effect of multiple reflections on the intensity of global radiation, especially in the cold part of the year when the albedo of the earth's surface varies within broad limits (from 0.05 to 0.80). This is well supported by the data of Table 4 which compares the thickness of St and Sc as determined from the data of aircraft soundings and by the technique proposed here. Let us examine two of the many examples given, viz., 2 February 1958 and 20 April 1958. In both cases, the altitude of the sun was the same ( $18.1^\circ$ ). The Sc was observed to be 850 m thick in the first case and 230 m thick in the second case. Accordingly, one would expect a substantial increase in the intensity of global radiation in the second case. However, Table 4 shows that the quantities  $Q_{s,a}$  were equal in both cases. The reason for this is that in the second case, the increase in the global radiation caused by the

decrease in the thickness of the cloud cover was cancelled by its decrease caused by the change in the albedo from 0.81 to 0.20. After  $Q_{s,a}$  has been reduced to zero albedo at the earth's surface, we obtain the quantity  $Q_{s,o}$  which agrees well with the thickness of the clouds, i. e., 0.036 cal/cm<sup>2</sup> min in the first case and 0.079 cal/cm<sup>2</sup> min in the second. All this indicates that it is impossible to obtain a reliable quantitative curve of  $Q_{s,a}$  vs. H without allowing for the effect of albedo on the intensity of global radiation.

The intensity of global radiation vs. the thickness of St and Sc was determined as follows. The quantities  $Q_{s,a}$  were reduced by formula (4) to values of  $A_e = 0$ . Then, all the cases for a given type of cloud cover (St or Sc) were divided into range intervals of  $Q_{s,o}$  (0.000-0.010; 0.011-0.020 etc. cal/cm<sup>2</sup> min). The width of an interval varied somewhat, depending on the magnitude of  $Q_{s,o}$  and the number of cases in a given interval. For each interval, the average magnitude of  $Q_{s,o}$  was determined and the thickness of the clouds H was plotted as a function of the altitude of the sun  $h_{\odot}$ . Here, there was a substantial scatter of the points, but the required dependence was shown quite accurately. One of the reasons for the scatter of points was the variation of  $Q_{s,o}$  within an interval. It would be possible to eliminate the effect of this factor by narrowing the intervals, but the authors were limited to a comparatively small number of cases. Tables 5 and 6 give the results of schematic averaging. The data of Tables 5 and 6 were used to plot the nomograms (Figures 1 and 2). In addition, they are of independent interest, because they can be used to compute the coefficients of the attenuation of global radiation by clouds, to determine the dependence of these coefficients on the altitude of the sun, etc.

**Table 4**

**Examples of Determination of the Thickness of St and Sc by Nomograms**

Date	Cloud Type	$h_{\odot}$ , degrees	$Q_{s,a}$ cal/cm <sup>2</sup> min	$Q_{s,o}$ cal/cm <sup>2</sup> min	$A_e$	$A_{cl}$	Aircraft data	Cloud thickness	
								Determination by nomogram	
								For specific $A_{cl}$	For mean $A_{cl}$
8 II 1962	Sc	8.2	0.033	0.022	0.61	0.54	360	540	410
7 XII 1957	Sc	8.2	0.035	0.024	0.60	0.52	200	560	570
16 II 1953	St	8.5	0.060	0.038	0.50	0.70	620	360	350
29 IV 1958	Sc	8.6	0.032	0.026	0.22	0.79	500	490	490
20 XII 1959	Sc	8.7	0.100	0.069	0.68	0.46	160	210	270
5 I 1962	Sc	8.8	0.060	0.036	0.48	0.84	640	400	380
10 XII 1961	St	8.8	0.050	0.036	0.19	0.44	180	290	320
25 XII 1960	St	8.8	0.032	0.041	0.05	0.61	450	360	360
21 X 1956	Sc	8.8	0.066	0.035	0.22	0.77	440	280	280
25 XI 1960	St	11.6	0.062	0.044	0.48	0.62	460	420	450
10 II 1961	Sc	11.9	0.180	0.112	0.34	0.63	300	130	150
16 I 1960	Sc	12.0	0.076	0.045	0.90	0.82	580	720	610
18 II 1960	Sc	12.1	0.132	0.098	0.58	0.47	150	200	260
17 I 1960	Sc	12.1	0.097	0.041	0.80	0.72	400	480	480
5 II 1960	St	12.4	0.100	0.074	0.68	0.38	140	330	400
30 X 1962	Sc	16.3	0.072	0.063	0.11	0.79	500	460	460
25 I 1958	Sc	16.4	0.130	0.052	0.81	0.74	430	500	530
6 II 1962	St	16.4	0.062	0.049	0.44	0.85	1010	800	710
7 X 1955	Sc	16.6	0.072	0.068	0.09	0.69	340	410	410
8 II 1962	St	16.8	0.119	0.092	0.48	0.48	220	410	490
8 III 1955	St	16.8	0.085	0.049	0.64	0.66	470	650	650
24 X 1962	Sc	17.9	0.088	0.078	0.14	0.81	560	440	430
9 III 1954	Sc	18.1	0.065	0.058	0.13	0.80	500	550	540
2 II 1958	Sc	18.1	0.120	0.046	0.81	0.85	820	730	600
20 IV 1958	Sc	18.1	0.120	0.105	0.20	0.62	230	340	350
22 III 1958	Sc	18.1	0.100	0.079	0.25	0.85	650	450	430
11 XI 1956	Sc	18.2	0.162	0.091	0.75	0.60	270	390	440
23 X 1962	Sc	18.3	0.055	0.046	0.22	0.79	500	650	650

The nomograms (Figures 1 and 2) show the magnitudes of global radiation  $Q_{s,o}$ , reduced to zero albedo at the surface of the earth, as a function of the thickness of St and Sc at various altitudes of the sun. The data on the intensity of global radiation in the absence of clouds ( $Q_{\odot}$ ), used when plotting the nomograms, was determined from the function  $Q_{\odot} = f(H)$ . The latter was obtained from the results of [2].



The nomograms (Figures 1 and 2) are intended to be used to determine the average thickness of St and Sc from ground-based actinometric observations.

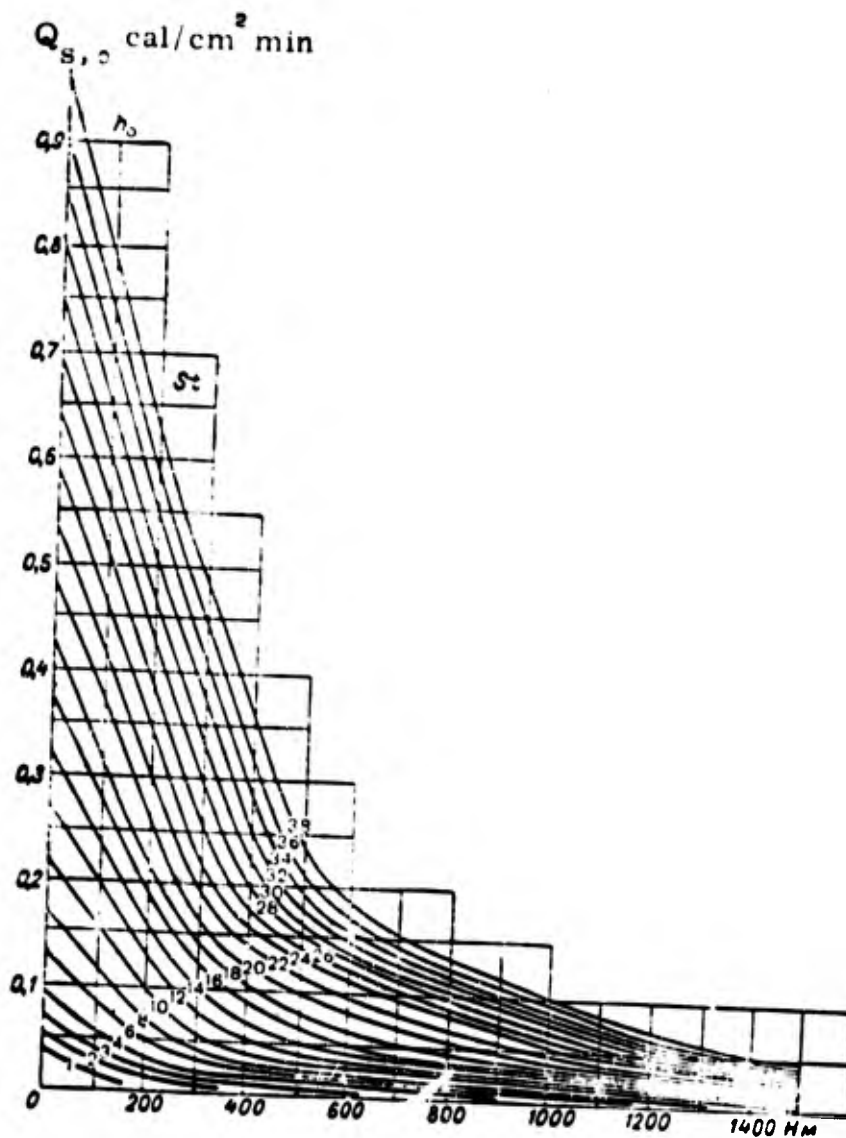


Figure 1. A nomogram for determination of the thickness  $H$  of St on the basis of ground-level data on the intensity of global radiation  $Q_{S,0}$ , reduced to zero albedo at the surface of the earth.

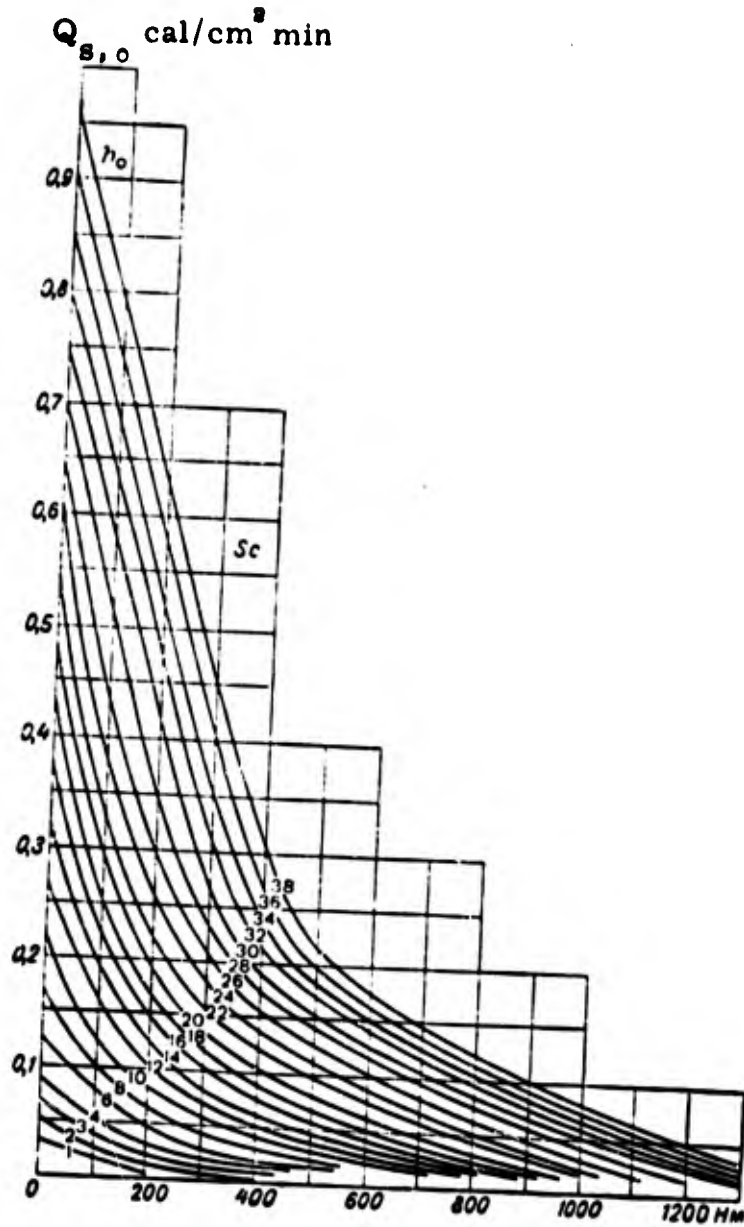


Figure 2. A nomogram for determination of the thickness,  $H$ , of  $Sc$  based on ground-level data on the intensity of global radiation  $Q_{s,0}$ , reduced to zero albedo at the earth's surface.

The magnitudes of  $H$ , as determined from the nomograms ( $H_n$ ) and from the data of aircraft soundings ( $H_a$ ), are compared in the correlation graph (Figure 3). This graph shows that the magnitudes of  $H_n$  and  $H_a$  agree well on the average over the entire range of variation in the thickness of St and Sc. The difference between their mean arithmetic values was 10 m, while the distribution curve of the discrepancies between them was close to a Gaussian curve. Thus, all the discrepancies between  $H_n$  and  $H_a$  are random.

The coefficient of correlation between  $H_n$  and  $H_a$  is 0.72 on the average (0.76 for St and 0.69 for Sc), which indicates a rather close relationship between the thickness of clouds and the intensity of global radiation at the surface of the earth.

However, Figure 3 shows that the scatter of points in the graph relating  $H_n$  to  $H_a$  is quite substantial. The mean square deviation between  $H_n$  and  $H_a$  equals  $\pm 170$  m, which is more than 30% for the average thickness of about 500 m.

In our opinion, one of the reasons for this scatter of points is that the thickness of the cloud layer, as determined from the data of aircraft soundings, and the thickness, as determined from the intensity of global radiation, are different quantities. We are dealing with local values of the thickness in the first case, while in the second case, we are dealing with a quantity that characterizes the average thickness of the cloud layer in the region above a given point. Observations of the position of the tops and bases of St and Sc during horizontal aircraft soundings show that although the level of the top is comparatively constant (it varies by about 50 m on the average), the spatial variations in

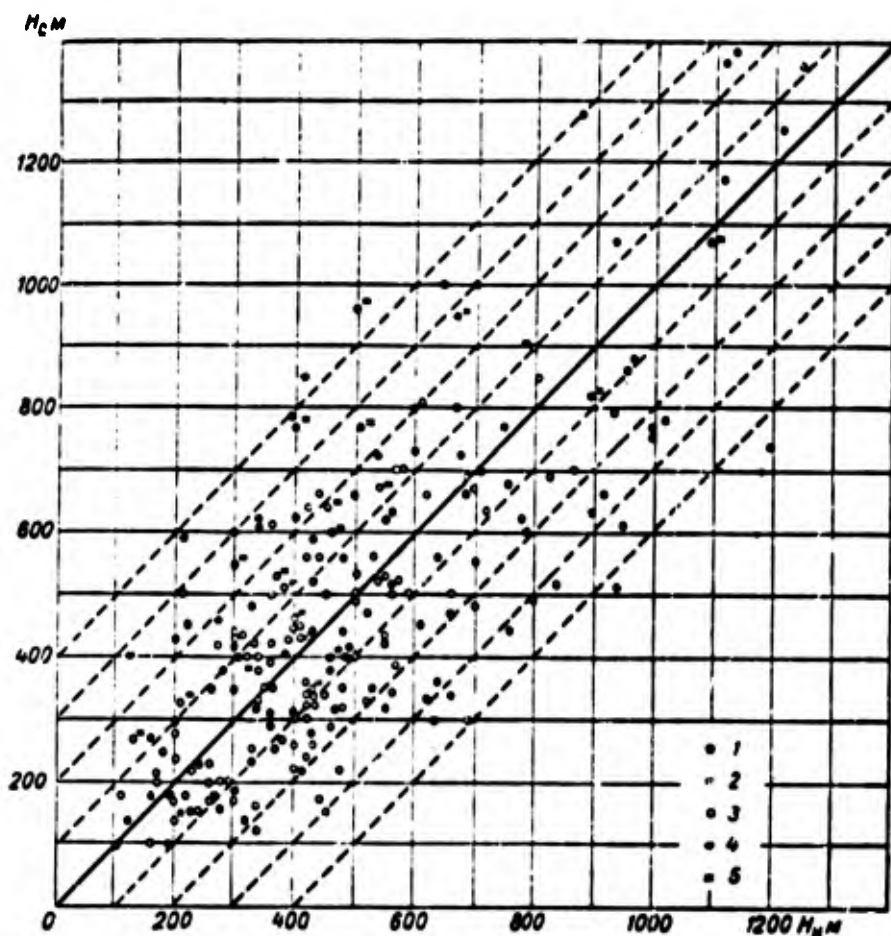


Figure 3. Correlation dependence between the thicknesses of St and Sc, as determined from the nomograms ( $H_n$ ) and from the data of aircraft soundings ( $H_a$ ).

1. Droplet phase St; 2. mixed phase St and Sc;
3. droplet phase Sc; 4. crystalline phase St and Sc; 5. two-layer clouds.

the height of the base are more substantial and sometimes exceed 100 m. The latter fact is completely natural because, according to the data of [11], St and Sc are subinversion clouds as a rule. Therefore, turbulent exchange develops under the cloud during the daytime

and, consequently, the height of the St or Sc bases may substantially vary in time and space. At the same time, turbulent exchange is greatly weakened above the tops of St and Sc because of the presence of inversion or isothermy. The aforementioned shows that a substantial difference is possible between the local and average characteristics of the thickness of the cloud layer. It is not possible to obtain a reliable quantitative evaluation of this difference from our data. However, it can tentatively be assumed that it is no less than 100 m.

Thus, we can conclude that the data on the average thickness of a cloud layer, derived from the intensity of global radiation at the surface of the earth, is a more reliable index of this quantity than the results of local aircraft measurements (even if the local results are accurately obtained).

There are also other reasons for the differences between  $H_n$  and  $H_a$ . These are deficiencies in the technique for determining the thickness of clouds from the data of aircraft soundings, primarily caused by errors in determining the position of the base and the time difference in observing the base and top of the cloud layer.

Research done by L. V. Dubrovin [4] shows that the accuracy of all the instrumental methods, including aircraft methods, of determining the height of the bases of low clouds does not exceed  $\pm 100$  to 150 m. Thus, according to his data, the height of the base up to 300 m, determined in the daytime by aircraft observations, must be systematically reduced by 100-200 m. This happens because the base is determined by the loss of visibility of the horizon, while the latter is lost not at the base of the cloud, but much lower. When the base is higher,

this error is reduced. It is possible that Dubrovin has overestimated the errors appearing in the aircraft method of determining the position of the base of low clouds, but even if they are reduced by half, they are still substantial (50 to 100 m). A reliable determination of the base is completely impossible in some cases, especially in the presence of precipitation or crystalline phase clouds.

The difference between the time that the aircraft enters the cloud and the time that it leaves the cloud must also result in marked errors in the determination of the thickness of the cloud layer. Summing up all the foregoing, we may conclude that the error of determination of the average thickness of the cloud layer from the data of aircraft soundings is about  $\pm 150$  m. Therefore, the resulting root-mean-square deviation between  $H_n$  and  $H_a$ , equal to  $\pm 170$  m, is completely reasonable and should not be ascribed to deficiencies in the proposed technique, but to the inaccuracy and unreliability of aircraft data as an index of the average thickness of a cloud layer above the observation station.

One deficiency of the proposed method is that it does not allow for the phase state of the clouds, the possibility that they have a multilayer structure, the difference in their liquid-water contents, and their microstructure. Individual examples in [7] show that an increase in the liquid-water content of a cloud at a given thickness is accompanied by a substantial increase in the albedo of the cloud top and, consequently, by a more intense attenuation of the global radiation. As a result, clouds with the same thickness but different liquid-water contents will have different values of  $H$  according to the proposed program. An analysis of Figure 3 gives some idea of how the phase state and multilayer structure of the cloud layer affects the results of the determination of the thickness by

the proposed technique. That Figure shows that in the overwhelming majority of crystalline phase and mixed phase clouds and in the case of two layers of St and Sc, the magnitudes of  $H_n$  are less than those of  $H_a$ .

The following data are required to determine the thickness of St and Sc on the basis of the proposed program: reliably measured values of the global radiation (to an accuracy of about  $0.005 \text{ cal/cm}^2 \text{ min}$ ), the albedo of the earth's surface (to an accuracy of 0.01), and the altitude of the sun (to an accuracy of  $1^\circ$ ). According to formula (4), the measured magnitude of global radiation,  $Q_{s, a}$ , must be reduced to zero albedo at the earth's surface  $A_e = 0$ . However, to use that formula, one must know the albedo of the cloud, whose magnitude depends on the thickness  $H$ , which is unknown. In this connection, we suggest that  $Q_{s, a}$  be reduced to  $A_e = 0$  by using the weighted mean value of the albedo of St and Sc. By using the data of Table 2, we obtained  $\bar{A}_{cl} = 0.64$  for St and  $\bar{A}_{cl} = 0.72$  for Sc. Correction factors (Table 7) were computed so that formula (4) would not have to be used each time. For a known albedo value at the surface of the earth,  $A_e$ , we find the corresponding multiplier in Table 7 and, if we multiply that by the measured magnitude of global radiation, we obtain  $Q_{s, o}$ . By means of the nomograms, we can determine the unknown value of the thickness of the cloud layer using  $Q_{s, o}$  and  $h_o$ . Examples of this computation are given in Table 6. It should be noted that the values of  $Q_{s, o}$  given in Table 6 correspond to the values of  $A_{cl}$  as determined from Chel'tsov's data with allowance for the thickness of the clouds.

The final result is somewhat different if quantity  $A_{cl}$ , which corresponds to a given thickness  $H$ , is replaced by the weighted mean  $\bar{A}_{cl}$ .

Table 7

Multipliers for Reducing the Measured Magnitudes of Global Radiation,  $Q_{s, a}$ , to Zero Albedo Value at the Earth's Surface ( $Q_{s, o}$ )

	0,00	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
<b>St</b>										
0,0	1,000	0,993	0,987	0,980	0,974	0,968	0,961	0,954	0,948	0,941
0,1	935	928	922	915	909	902	896	890	883	876
0,2	870	863	857	850	844	837	830	825	818	811
0,3	805	799	796	786	778	772	766	760	752	746
0,4	740	733	726	720	713	708	700	694	688	682
0,5	674	668	662	653	646	642	636	630	622	616
0,6	609	603	598	591	585	578	571	565	558	552
0,7	545	538	532	526	520	513	506	500	494	487
0,8	480	473	468	461	454	448	441	435	429	422
0,9	416	409	402	395	389	383	376	370	364	357
<b>Sc</b>										
0,0	1,000	0,993	0,986	0,979	0,972	0,964	0,957	0,950	0,942	0,935
0,1	928	921	915	906	899	892	885	878	870	863
0,2	856	849	842	833	827	820	812	805	798	791
0,3	783	777	770	762	755	748	741	734	727	720
0,4	712	704	697	690	683	676	669	662	654	647
0,5	640	632	626	618	611	604	597	590	583	575
0,6	568	561	554	547	540	532	525	518	510	503
0,7	496	488	481	474	467	460	453	445	438	431
0,8	424	417	410	403	395	388	381	374	367	360
0,9	352	345	337	330	323	316	308	300	292	284

But Table 6 indicates that this change is not great. The data of Table 6 were used to compute the root-mean-square deviations between  $H_a$  and  $H_n$  when  $H_n$  was determined from cloud albedos derived both with ( $A_{cl}$ ) and without ( $\bar{A}_{cl}$ ) allowance for the thickness of the clouds. The results showed a deviation of  $\pm 159$  m for the first case and  $\pm 171$  m for the second case. The root-mean-square deviation between  $H_n$  and  $H_a$  obtained by both methods is  $\pm 50$  m. Thus within the limits of accuracy of this technique, the average thickness of the cloud layer can be calculated from the average albedo values of St and Sc (without allowing for  $A_{cl}$  vs. H).

Some information on the radiation properties of St and Sc can be obtained on the basis of  $Q_{s,0}$  vs.  $H$ . It is indicated in [7] that the transmission of radiation by clouds can be represented as an exponential function from which it is easy to derive a formula for computing the coefficient of total attenuation of radiation,  $k$ , (in  $m^{-1}$ )

$$k = \frac{\ln \frac{Q_{s,0}}{Q_0}}{H} \quad (13)$$

This coefficient allows for both the reflection of radiation from the cloud top and its absorption in the cloud layer. Therefore, the coefficient  $k$  can be represented as the sum of two components, viz.,

$$k = k_{\text{ref}} + k_{\text{abs}} \quad (14)$$

According to formula (13),  $\ln Q_{s,0} / Q_0$  is a linear function of  $H$ . A formulation of this function on the basis of our data showed that it can only be considered linear as a rough approximation. This function consists of two linear parts for St: one up to  $H = 500$  m and the other for  $H > 500$  m. The average value of  $k$  substantially differs for each of these parts. All this indicates that the coefficient of total attenuation is not a constant. Its value depends on many factors, especially the altitude of the sun and the thickness of the cloud layer.

Formula (13) was used to derive values of  $k$  for St and Sc of different thicknesses at various altitudes of the sun. Then we plotted the function  $k$  vs.  $H$  (for  $300 \text{ m} \leq H \leq 600 \text{ m}$ ) and the function  $k$  vs.  $h_0$  (for  $h_0 \sim 18-22^\circ$ ) (Figure 4).

Figure 4 shows that  $k$  decreases monotonically as  $h_0$  increases. This type of dependence of  $k$  on  $h_0$  is determined by the variation in the

path length of the sun's rays in the cloud layer and by the dependence of the albedo at the cloud top on the angle of incidence of the rays. It was stated above that at present there are no experimental data for the dependence of the albedo of clouds on  $h_{\odot}$ . However, theoretical calculations made by E. M. Feigel'son show [13] that this dependence exists and that it is rather substantial. In [13] the albedo found for St and Sc 500 m thick decreased by 0.028 (St) and 0.022 (Sc) when  $h_{\odot}$  was increased by  $10^{\circ}$ . A preliminary computation based on these data shows that this change in the albedo causes  $k$  to be reduced by about  $0.9 \times 10^{-3} \text{ m}^{-1}$  for St and by  $0.8 \times 10^{-3} \text{ m}^{-1}$  for Sc when  $h_{\odot}$  increases from  $10$  to  $40^{\circ}$ . Figure 4 shows that the actual change in  $k$  under these conditions is  $1.20 \times 10^{-3} \text{ m}^{-1}$  for St and  $1.35 \times 10^{-3} \text{ m}^{-1}$  for Sc. This substantially exceeds the possible changes caused by a reduction in the albedo. The remaining portion of the change in  $k$  is evidently caused by a reduction in the path length of the sun's rays in the cloud.

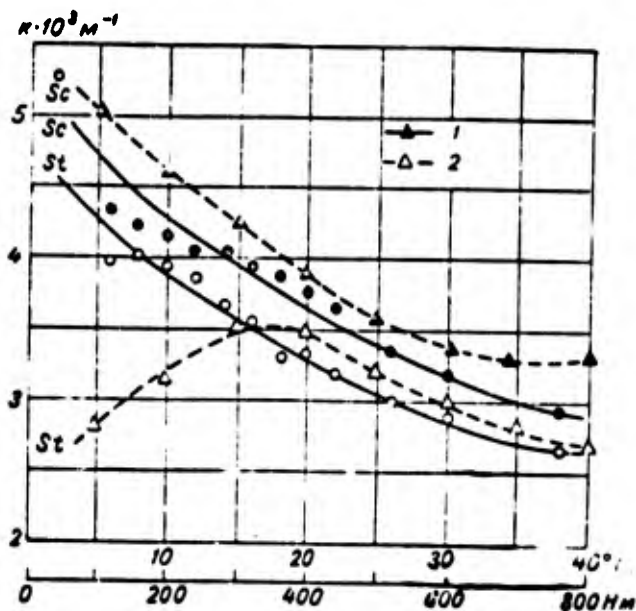


Figure 4. The coefficient of the total attenuation of radiation by St and Sc as a function of the altitude of the sun  $h_{\odot}$  (1) and as a function of the thickness of the cloud layer  $H$  (2).

Figure 4 shows that the dependence of  $k$  on the thickness of the cloud (when the altitude of the sun is constant) is more complex than its dependence on  $h_c$  examined above. Thus, for Sc, a constant decrease of  $k$  is observed as the thickness of the cloud layer increases. For St,  $k$  initially increases, reaching a maximum value at  $H \sim 300-400$  m and then, like Sc, it constantly decreases. When the thickness exceeds 700 m, the change in  $k$  becomes less as  $H$  increases, while for Sc the value of  $k$  remains practically constant. The reason for such a complex relationship of  $k$  with  $H$  is the distinctive interaction of factors (the albedo and absorption capacity of the cloud) caused by the change in  $k$ . In order to clarify the role of the cloud's albedo, let us assume that the absorption capacity and, consequently,  $k$  do not depend on the thickness of the cloud layer. Then the reflection of radiation from the cloud top will be responsible for all changes in  $k$ . In that case, the value of  $k$ , strictly owing to the increase in  $H$ , must decrease since the attenuation of radiation due to reflection will be distributed over a greater thickness. On the other hand, an increase in the thickness of a cloud is accompanied by an increase in its albedo and this must result in an increase in  $k$ . The effect of the latter factor is most substantial for an increase of thickness up to 400 m. After that,  $A_{cl}$  changes insignificantly as  $H$  increases and the role of the first factor becomes predominant. In addition, one must bear in mind that our assumption that the absorption capacity is independent of cloud thickness is not actually valid because a change in the thickness is accompanied by a change in the liquid-water content and microstructure. Thus, the data of I. P. Polovina [10] shows that the average liquid-water content of St and Sc may increase by a factor of five to eight when the thickness of the cloud layer increases from 100 to 600 m. The temperature conditions of a

cloud also have a significant effect on the average liquid-water content. The mechanism of the dependence of a cloud's absorption capacity on all these factors has not yet been adequately studied and thus it is difficult to predict how these factors effect the magnitude of the coefficient of total attenuation of global radiation. In view of the foregoing, it becomes apparent that various types of curves are possible for  $k$  vs.  $H$ . Consequently, the results that we obtained for the dependence of coefficient  $k$  on the altitude of the sun and especially, on the thickness of the cloud layer should be directly and experimentally verified by measurements of the global radiation from an aircraft.

### Conclusions

1. A rather close relationship (with correlation coefficient of 0.72) is found between the intensity of global radiation at the earth's surface and the thickness of  $St$  and  $Sc$  determined from the data of aircraft soundings.
2. The nomograms proposed in the present paper permit us to determine reliably and with adequate accuracy the average thickness of  $St$  and  $Sc$  above the observation station.
3. The quantitative characteristics of the relationship between the intensity of global radiation and the thickness of the cloud layer permitted us to obtain some information on the radiation properties of  $St$  and  $Sc$ . Specifically, it was established that the coefficient of total attenuation of the global radiation essentially depends on the altitude of the sun and the thickness of the cloud layer. The possible differences

between the albedos at the top and base of clouds is tentatively evaluated. These differences are most significant (0.05-0.09) for clouds up to 200 m in thickness. When the thickness of the cloud layer is greater than this, these differences are rapidly reduced and both quantities are practically equal. It should be noted that for the direct radiation, no allowance was made here for the dependence of the albedo of the cloud top for direct radiation, on the angle of incidence of the sun's rays.

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