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FOREIGN TECHNOLOGY DIVISION

ON THE QUESTION OF CALCULATIONS OF THERMAL RADIATION OF THE ATMOSPHERE

By

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ON THE QUESTION OF CALCULATIONS OF THERMAL RADIATION OF THE ATMOSPHERE

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ABSTRACT: At present three methods for computing radiation fluxes of the atmosphere exist: theoretical formulas, empirical formulas, and graphic methods. Since empirical formulas are true only for average conditions of the atmosphere and calculations with theoretical formulas are connected with large calculation difficulties, many authors have tried to find graphic methods for calculating atmospheric radiation fluxes which would allow simplifying computations and simultaneously correctly considering the concrete atmospheric conditions. Such methods are called radiation monographs.

Now since there are several radiation monographs based on different principles, their study and comparison is of interest. Such a study enables clarifying the cause of divergent results and attempting the evaluation of the advantages and disadvantages of individual monographs, which is the basic purpose of this work. By using aeroclimatic data for various global zones, an attempt is made in this work to obtain average typical data about the movement of thermal radiation fluxes at different latitudes and heights in the troposphere.

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Block	Italic	Transliteration	Block	Italic	Transliteration
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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

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FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

ON THE QUESTION OF CALCULATIONS OF THERMAL RADIATION OF THE ATMOSPHERE

Khel'gi Niylisk

Introduction

At present there exist three methods of computing radiation fluxes of the atmosphere: theoretical formulas, empirical formulas, and graphic methods. Since empirical formulas are true only for average conditions of the atmosphere and calculations with the help of theoretical formulas are connected with large calculating difficulties, many authors have tried to find graphic methods for calculation of atmospheric radiation fluxes, which would allow to simplify the calculations and simultaneously correctly consider the concrete conditions in the atmosphere. As is known, such graphic methods are called radiation nomographs.

Since at present there exists a whole series of radiation nomographs based on different principles, their comparison and also their study is of considerable interest. Study of the nomographs enables one to clarify the cause of the divergence of results and thus to this or that degree to try to evaluate the advantages and deficiencies of individual nomographs. This is the basic purpose of this work. Besides this, by using average aeroclimatic data for various zones of the globe we will try in this work to obtain average typical data about the movement of fluxes of thermal radiation on different latitudes and heights in the troposphere.

Brief Characteristics of Radiation Nomographs

During the construction of radiation nomographs all authors originate from the equation of the transfer of long-wave radiation [1, 2]:

$$\left.\begin{aligned} \frac{\cos\theta}{\rho_m}\cdot\frac{\partial I_\lambda\uparrow(z,\theta)}{\partial z} &= k_\lambda[I_\lambda\uparrow(z,\theta) - E_\lambda], \\ \frac{\cos\theta}{\rho_m}\cdot\frac{\partial I_\lambda\downarrow(z,\theta)}{\partial z} &= k_\lambda[E_\lambda - I_\lambda\downarrow(z,\theta)]. \end{aligned}\right\} \qquad (1)$$

It is found that after approximate solution of these equations the expression for fluxes of radiation can, by one or another means, be presented in the form

$$G = \oint M dN, \qquad (2)$$

where M and N are certain known functions.

Fluxes of thermal atmospheric radiation will be numerically equal to the area in the system of coordinates (M, N).

Expressions for fluxes of radiant energy constitute triple integral over all wavelengths over all solid angles composing the hemisphere and over all elementary layers composing the final layer for which radiation is calculated. The distinction between nomographs consists in the order and methods of their integrations and also depends on the utilized experimental data of absorbed long-wave radiation, i.e., on the transmission function. Of essential value is not only the quantitative distinction of transmission functions but also the fundamental approach to them, depending upon the quantities determining them. As is known, the transmission of thermal radiation by the atmosphere depends not only on the content of substances absorbing radiation in the atmosphere but also on the structure of layers which absorb radiation. Therefore the transmission function should be presented in the form

$$P_S = P_S(m, p, T). \tag{3}$$

Thus the difference between radiation nomographs consists still in the calculation of the dependence of transmission functions on pressure and temperature.

It is necessary to note that without exception all the authors of radiation nomographs consider the dependence of the transmission functions on pressure not directly, but indirectly, by introducing the so-called "effective absorbing mass." In otherwords, instead of the ordinary expression for the absorbing mass

$$m = \int \rho_w dz, \tag{4}$$

they apply the formula

$$m^* = \int \rho_w f(p) dz. \tag{5}$$

We know of seven radiation nomographs, by the following authors: Shekhter [3, 4], Dmitriyev [5], Brooks [6], Robinson [7], Elsasser [8], Yamamoto [9], and Mügge and Möller [1, 10, 11].[1] Let us consider briefly the basic principles of these nomographs.

[1]Another radiation nomograph was developed by Deacon [12], but it is intended for calculation of thermal flux only in the surface layer of the atmosphere.

The simplest principle of construction of radiation nomographs was used by Shekhter, Brooks, and Robinson. These authors considered the dependence of the transmission function only on the effective content of water vapor, i.e., they presented the transmission function in the form

$$P_D = P_D(w), \tag{6}$$

where

$$w = \int \rho_w \sqrt{\frac{p}{p_c}}\, dz. \tag{7}$$

Here p_c designates a certain standard pressure.

A more general principle of the construction of radiation nomographs was applied by Dmitriyev, Elsasser, Yamamoto and also by Mügge and Möller. They tried to consider the influence of temperature on absorption of long-wave radiation.

As is known, the integral transmission function can be expressed as follows:

$$P_D = \int_0^\infty f_\lambda(T)\, P_{\lambda,D}[k_\lambda(T, p), w]\, d\lambda. \tag{8}$$

The influence of the temperature of the absorbing medium on the absorption of radiation appears in twofold form. On the one hand, with a change in temperature in accordance with Wien's law there occurs a displacement of the distribution curve of energy in the spectrum of radiation of an ideal black body ("displacement effect"). A consequence of this is $f_\lambda = f_\lambda(T)$. On the otherhand, a change in the temperature of the absorbing medium is connected with a change in the intensity and width of lines and absorption bands. Therefore the coefficient of absorption k_λ should also be considered to be a function of temperature.

During the construction of their nomographs Dmitriyev, Elsasser, Mügge and Möller considered only the "effect of displacement": they considered coefficients of absorption to be independent of temperature. Yamamoto took the dependence of the coefficient of absorption on temperature into account. Therefore with respect to calculation of temperature effect Yamamoto's nomograph is the best developed.

For the effective content of water vapor Elsasser recommends using formula (7) and Yamamoto and Dmitriyev propose the following formula:

$$w = \int_0^z \rho_w \frac{p}{p_0} dz. \qquad (9)$$

Möller proposes taking a more complicated correction for calculation of the influence of pressure on infrared atmosphere radiation. He considers that in formula (5)

$$f(p) = 0{,}985 \left(\frac{p}{p_0}\right)^{\frac{4}{5}} + 0{,}015 \frac{p_0}{p}. \qquad (10)$$

Nomograph of F. N. Shekhter

In basis of construction of his nomograph Shekhter assumes general formulas for fluxes of thermal radiation obtained as the result of integration equations of transfer of radiation (1) by the method of Ambartsumyan and Lebedinskiy [2]. The concept of this method consists of the fulfillment of integration over all wavelengths in two stages. First integration is conducted in terms of those λ for which $k < k_\lambda < k + dk$ and then for all dk. Further there is introduced the function $f(k)$, determining the share of intensity of incident radiation occurring on those sections of the spectrum to which there correspond infinitesimally differing values of the coefficient of absorption, i.e., in those sections of the spectrum the coefficient of absorption is considered constant.[1]

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[1]Here Shekhter considered the function $f(k)$ to be independent of temperature.

For the descending radiation flux of the atmosphere Shekhter obtained

$$G\downarrow(w)=\int_{0}^{B(w)}P_D(0)dB+\int_{B(w)}^{B(w_{0,\infty})}P_D(w)dB+$$
$$+\int_{B(w_{0,\infty})}^{B}P_D(w_{0,\infty})dB=\oint P_D(w)dB. \qquad (12)$$

The rising flux of thermal radiation can be determined analogously.

As can be seen from formula (12), the thermal fluxes at a given level are numerically equal to the area bounded by a closed contour in the system of coordinates $\left(P_D, B\right)$.

During construction of the transmission function P_D, Shekhter considers the influence of two atmospheric gases — water vapor and carbon dioxide — on the absorption of thermal radiation; this means that $P_D = P_D(w, u)$. She assumes that

$$P(w, u) = P(w) - P(w)_{13-17}\cdot A(u)_{13-17}. \qquad (13)$$

Here the exponent "13-17" shows that the function of transmission or absorption is given only for the 13-17 μ region of the spectrum.

Further, Shekhter finds a connection between u and w (with an average content of carbon dioxide):

$$u = 160{,}3\left[1-\left(1-\frac{w}{1{,}36}\right)^{\frac{3}{7}}\right]. \qquad (14)$$

By substituting expression (14) in formula (13) we will obtain the transmission of long-wave atmospheric radiation in dependence upon only one variable — the effective content of water vapor, w. Shekhter proposed a special nomograph for computing w. However, in the form in which it is given in work [7] this auxiliary nomograph gives results which do not correspond to formula (7); apparently there is a misprint here.

During construction of the transmission function P_D Shekhter used experimental and theoretical data of many authors on absorption by water vapor and carbon dioxide [3]. The obtained curve turned out to be in good approximation to the formula

$$P_D(w) = Q_1 H_6(q_1, \sqrt{w}) + P_1 H_6(p_1, \sqrt{w}). \qquad (15)$$

Shekhter determined the values of the coefficients: $Q_1 = 1.884$; $P_1 = 2.116$; $q_1 = 0.54$; $p_1 = 6.94$.

Nomograph of F. Brooks

Brooks' nomograph is built on the assumption that in the coordinate system $\left[\left(1 - \varepsilon_D\right), B\right]$ thermal fluxes of the atmosphere are expressed by areas,[1] i.e.,

$$G(w) = \oint (1 - \varepsilon_D)\, dB, \qquad (16)$$

Brooks experimentally determined emittance $\varepsilon(w, u)$ for parallel radiation. Observations were produced in the laboratory and in the Earth's atmosphere (in a winter continental-polar air mass which contained a normal quantity of carbon dioxide). Thus, during the determination of the magnitudes of w and $\varepsilon(w)$ the influence of carbon dioxide on emittance ε in the given air mass was automatically considered. The coefficient of diffusivity was determined experimentally in order to obtain the emittance for diffuse radiation; it turned out to be equal to 1.73. The curve $\varepsilon_D = \varepsilon_D(w)$ was obtained with account taken of the influence of carbon dioxide on the transmission of radiation (on the assumption that the content of carbon

[1]Brooks used the fact that in an isothermal atomosphere $P = 1 - \varepsilon$.

dioxide corresponds to conditions of a winter continental-polar air mass).

Nomograph of G. Robinson

Robinson, like Brooks, considers that fluxes of thermal radiation in the atmosphere are expressed numerically by areas in the coordinate system $\left[\left(1 - \varepsilon_D\right), B\right]$. The only difference is that Robinson considers the influence of carbon dioxide on atmospheric radiation fluxes separately from the influence of water vapor. He assumes that the radiation of carbon dioxide always composes 18.5% of the radiation an ideal black body at a temperature of the air at the earth's surface such that

$$G(w) = 0.185B_0 + \oint [1 - \varepsilon_D(w)]dB. \quad (17)$$

Using measurements of the emittance of isothermal layers of the atmosphere carried out by different authors, as well as his own, Robinson constructed the curve of the dependence of emittance of the isothermal layers of the atmosphere on their absorbing mass for parallel radiation. Then he constructed a curve with taking into account diffusivity of radiation, where the coefficient of diffusivity was assumed equal to 1.66.

Nomograph of A. A. Dmitriyev

At the basis of the nomograph of Dmitriyev lies the most general examination of the problem of transfer of long-wave radiation in the atmosphere. In this case the determination of radiation fluxes are produced in three stages, for which there are three corresponding nomographs: one basic and two auxiliary. First — an auxiliary nomograph — permits considering the dependence of the absorption of thermal radiation in the atmosphere on pressure and serves for calculation of effective absorbing masses of water vapor. With the help of the second — the basic nomograph — the intensity of radiation for different directions is calculated. By solving the general equations of radiative heat transfer, Dmitriyev obtained the following formula for the intensity of descending radiation:[1]

$$I\downarrow(w,\vartheta)=\int_{R_B(T,w)}^{R_B(T_1,w)}\frac{R(T,w)}{R(T_1,w)}\,dR_B(T_1,w), \tag{18}$$

where

$$R(T,w)=\int_0^\infty k_{\lambda,c}E_\lambda(T)e^{-k_{\lambda,c}w}\,d\lambda \tag{19}$$

and

$$R_B(T,w)=\int_0^\infty E_\lambda(T)e^{-k_{\lambda,c}w}\,d\lambda \tag{20}$$

when $T_1 = 273^\circ K$.

In formulas (19) and (20) $k_{\lambda,c}$ designates the coefficient of absorption at standard pressure p_c.

Dmitriyev obtained an analogous formula for $I\uparrow$

The third — an auxiliary nomograph — serves for calculation of total fluxes of thermal radiation in a hemisphere by the formulas:

$$\left.\begin{aligned} Q\downarrow(w)&=2\pi\int_0^{\frac{\pi}{2}} I\downarrow(w,\vartheta)\,d\left(\frac{\sin^2\vartheta}{2}\right),\\ Q\uparrow(w)&=2\pi\int_0^{\frac{\pi}{2}} I\uparrow(w,\vartheta)\,d\left(\frac{\sin^2\vartheta}{2}\right).\end{aligned}\right\}$$

During construction of the transmission function Dmitriyev used the exponential law

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[1] It is necessary to note that the results of calculations by the nomographs of Dmitriyev and also Mügge and Möller do not depend on the selection of temperature T_1.

$$P_\lambda = e^{-k_\lambda c w}. \tag{22}$$

Integration over all wavelengths was carried out within the limits $4.5\,\mu \leq \lambda \leq 92\,\mu$. Here the entire infrared spectrum was divided into 16 sections from 1 to 28 μ in width and it was assumed that in each of these sections absorption was constant. The coefficients of the sections were calculated according to Albrecht and Elsasser. The influence of carbon dioxide on the absorption of long-wave radiation is completely ignored by Dmitriyev.

<u>Nomograph of R. Mügge and F. Möller</u>

The nomograph of Mügge and Möller is based on the approximate solution of the problem of the transfer of long-wave radiation in the atmosphere. The basic principles of the nomograph are approximately the same as those for Dmitriyev nomograph No. 2.

On the nomograph of Mügge and Möller long-wave fluxes of atmospheric radiation are depicted in the coordinate system $\left[x\left(T_1, w\right), y\left(T, T_1, w\right)\right]$, so that

$$G(w) = \oint y(T, T_1, w)\, d[x(T_1, w)], \tag{23}$$

where

$$x(T_1, w) = \pi \int_0^w dw \sum_\lambda E_\lambda(T_1) \frac{\partial A(k', w)}{\partial w} \Delta\lambda, \tag{24}$$

$$y(T, T_1, w) = \frac{\sum_\lambda E_\lambda(T) \frac{\partial}{\partial w} A_D(k', w)\, \Delta\lambda}{\sum_\lambda E_\lambda(T_1) \frac{\partial}{\partial w} A_D(k', w)\, \Delta\lambda}, \tag{25}$$

$$A_D(k', w) = \frac{1}{\Delta\nu} \int_{-\frac{\Delta\nu}{2}}^{+\frac{\Delta\nu}{2}} \left[1 - 2H_3\left(\frac{k' w \frac{\beta}{4}}{(\nu - \nu')^2 + \frac{\beta^2}{4}}\right)\right] d\nu, \tag{26}$$

where ν' is the frequency corresponding to the center of the line, $T_1 = 313^\circ K$, κ' is the coefficient of absorption in the center of the line.

For construction of the function of absorption the authors use the average coefficients obtained by Albrecht. The coefficient of diffusivity is equal to 1.66.

A special auxiliary nomograph is proposed for calculation of the influence of carbon dioxide on atmospheric radiation. During construction of this auxiliary nomograph it was assumed that radiation of an isothermal layer of carbon dioxide at a temperature of $313^\circ K$ and containing an infinitely large quantity of CO_2 is 13.3% of the radiation of an ideal black body at the same temperature. If the change in the content of carbon dioxide with height is known, with the auxiliary nomograph one can determine the magnitude of radiation of carbon dioxide for any layer of the atmosphere.

Nomograph of W. Elsasser

By solving the general equations of transfer of long-wave radiation, Elsasser beforehand carries out integration in terms of all solid angles and all wavelengths and for integration in terms of all elementary layers he proposes a radiation nomograph. Radiation fluxes in the given case are numerically equal to areas in the coordinate system $\left(\frac{Q}{2\alpha T}, \alpha T^2\right)$, where

$$Q(w, T) = \int_0^\infty \frac{d[B_\lambda(T)]}{dT} P_0(l_\lambda, w)\, d\lambda. \qquad (27)$$

Here α is a certain constant.

Fluxes of thermal radiation are calculated graphically on the basis of the formula

$$G(w) = \oint \dot{Q}(w, T)\, dT. \qquad (28)$$

To carry out integration in terms of wavelengths Elsasser idealizes the absorption spectrum and introduces a so-called generalized coefficient of absorption l_λ. During calculation of these coefficients Elsasser used theoretical and experimental data of many authors on absorption by water vapor [8]. Elsasser considers radiation of carbon dioxide very approximately, considering that independently of the content of carbon dioxide, its radiation (in the interval 13-17 μ) can always be considered equal to a certain fraction of the radiation of an absolute black body at the temperature of the considered level.

Nomograph of G. Yamamoto

The equations which form the basis of the Yamamoto nomograph are the same in principle as those in the Elsasser nomograph, but Yamamoto transformed them somewhat. He selects another coordinate system, namely: as the abscissa, B(T) and as the ordinate, $P_D(w, T)$. For calculating the transmission function of water vapor Yamamoto used the Elsasser method, i.e., generalized coefficients of absorption $l_\lambda(T)$, but for the far infrared region he used other data about absorption by water vapor. Yamamoto also considered the dependence of l_λ on T.

Yamamoto considers the radiation of atmospheric carbon dioxide with the help of two special auxiliary nomographs. The first of them serves for calculation of the correction of the radiation of carbon dioxide $\Delta G\left[f_1(u, w)\right]$ in the 12.5-17.5 μ region of the spectrum on the total radiation flux. This nomograph is located in the lower part of the basic nomograph. With the help of the other auxiliary nomograph one can find the function $f_1(u, w)$ if u and w are known.

For construction of the transmission function of carbon dioxide $P_D(u, T)$ in the 12.5-17.5 μ region of the spectrum Yamamoto used Callender's data. The coefficient of diffusivity was taken as 1.5.

The dependence of the transmission function transmission for CO_2 on temperature was considered only at temperatures $T < 160^{\circ}K$. The transmission functions for water vapor and carbon dioxide $P_D(u, w)$ were calculated on the assumption that

$$P_D(u, w) = P_D(u) \cdot P_D(w). \qquad (29)$$

The transmission functions for all the named nomographs are shown in Fig. 1. But it is impossible strictly to compare these functions, since they are determined at different temperatures. For instance, the absorption function of the Mügge and Möller nomograph was obtained at a temperature of $313^{\circ}K$ and that of the Elsasser nomograph at $273^{\circ}K$. In the Yamamoto nomograph only the absorption function for water vapor is given, since Yamamoto considers the radiation of carbon dioxide separately with the help of a special nomograph. Owing to the various principles of construction of the nomographs in general, an exact comparison on the basis of the corresponding functions of absorption is impossible.

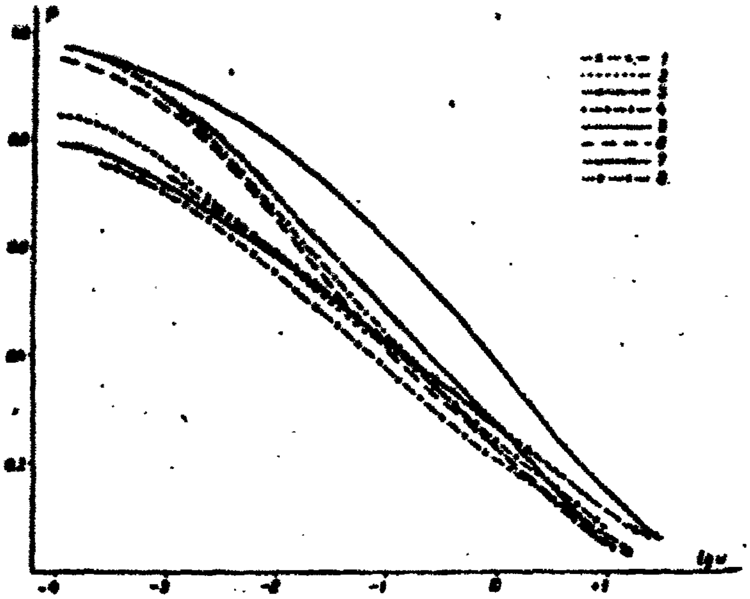

Fig. 1. Integral transmission function for nomographs: 1 — Elsasser (0°C); 2 — Mügge and Möller; 3 — Robinson; 4 — Brooks; 5 — Yamamoto; 6 — Shekhter; 7 — Dmitriyev; 8 — Elsasser (40°C).

Calculations by the Nomographs and Analysis of the Results

In this work calculations are performed according to all the above-described nomographs, with use of the following data:

a. Data of radiosounding of the atmosphere near the city of Tallin during 1958. Only data of cloudless days are selected.

b. Average typical aeroclimatic data in clear weather for various latitudinal zones of the globe, taken from works 9 and 13.

The principal characteristics of these data are shown in Tables 1 and 2.

Table 1. Temperature, Thickness of Inversion, and Total Content of Water Vapor[1] at the Earth's Surface

Date	Time	t_0 (°C)	Thickness of inversion (°C)	$w_{0,\infty}$ ("cm")
16. III 58	15.00	1.0	—	1.02
	21.00	−2.2	2.7	0.90
17. III 58	03.00	−4.5	4.0	0.94
18. III 58	21.00	−4.2	—	0.66
19. III 58	03.00	−9.0	2.8	0.51
	15.00	−2.5	—	0.27
20. III 58	03.00	−12.5	3.3	0.43
	15.00	−4.2	—	0.41
21. III 58	21.00	−8.5	—	0.51
22. III 58	03.00	−12.0	3.8	0.50
25. IV 58	03.00	−1.2	1.7	0.72
	15.00	5.5	—	0.71
	21.00	3.2	—	0.95
11. V 58	07.00	4.0	—	0.73
15. V 58	07.00	8.0	1.1	1.00
30. V 58	21.00	6.2	6.0	1.46
31. V 58	03.00	6.8	4.6	1.44
28. VIII 58	03.00	11.5	6.3	2.25
	15.00	19.8	—	1.97
	21.00	15.2	—	2.25
31. VIII 58	15.00	19.2	—	2.00
	21.00	14.8	2.1	2.20
1. IX 58	03.00	11.6	4.0	2.11

[1] Per formula (7).

Table 2. Temperature and Total Content of Water Vapor on the Earth's Surface in Various Zones of the Globe in March[1]

Latitudinal zone	t_0 (°C)	$w_{0,\infty}$ ("cm")
0—10° N	27.7	4.3
10—20° N	25.3	3.4
20—30° N	22.3	2.6
30—40° N	13.0	1.54
40—50° N	4.0	1.06
50—60° N	— 5.0	0.57
60—70° N	—14.3	0.28

[1] It is possible to consider these values close to the annual average.

With the help of the family of nomographs fluxes of thermal atmospheric radiation (descending flux, rising flux, and effective radiation) were determined at the level of the earth's surface and at 3 km. On the basis of the data in Table 2 radiation fluxes for the 8 km level were calculated. For determination of the effective absorbing mass of water vapor the formula recommended by the author of the corresponding nomograph was used (the only exception is the Mügge and Möller nomograph, for which effective absorbing masses were calculated by formula (7)).

The radiation of the earth's surface in all cases was calculated by the formula $B_0 = \delta T_0^4$.

The results of these calculations are presented in Tables 3-10 and in Figs. 2 and 3.

Besides this additional calculations were produced by the various nomographs to study the influence of the correction for pressure and for a more detailed determination of the movement of fluxes of thermal atmospheric radiation with height.

Table 3. Descending Radiation Fluxes on the Earth's Surface $G_0 \downarrow$ (cal/cm^2·min)

Date and time	Per nomograph of						
	Э	М	Ш	Б	Р	Я	Д
16. III 15	0.351	0.340	0.345	0.342	0.323	0.332	0.332
16. III 21	0.344	0.336	0.330	0.330	0.314	0.328	0.328
17. III 03	0.338	0.332	0.334	0.333	0.309	0.324	0.326
18. III 21	0.320	0.307	0.310	0.307	0.298	0.297	0.295
19. III 03	0.298	0.291	0.290	0.288	0.280	0.283	0.279
19. III 15	0.291	0.288	0.275	0.271	0.262	0.265	0.262
20. III 03	0.281	0.280	0.270	0.269	0.252	0.263	0.264
20. III 15	0.296	0.288	0.283	0.279	0.283	0.274	0.272
21. III 21	0.294	0.286	0.281	0.279	0.263	0.273	0.272
22. III 03	0.280	0.285	0.279	0.277	0.259	0.274	0.267
25. IV 03	0.340	0.332	0.336	0.333	0.311	0.327	0.324
25. IV 15	0.350	0.337	0.341	0.338	0.322	0.326	0.330
25. IV 21	0.364	0.352	0.361	0.357	0.335	0.346	0.350
11. V 07	0.361	0.350	0.356	0.354	0.331	0.342	0.343
15. V 07	0.411	0.400	0.411	0.413	0.382	0.396	0.400
30. V 21	0.456	0.404	0.409	0.409	0.377	0.396	0.396
31. V 03	0.409	0.406	0.409	0.410	0.389	0.398	0.398
28. VIII 03	0.452	0.445	0.460	0.462	0.436	0.440	0.455
28. VIII 15	0.460	0.458	0.472	0.473	0.441	0.453	0.459
28. VIII 21	0.461	0.447	0.467	0.469	0.432	0.446	0.451
31. VIII 15	0.472	0.452	0.478	0.479	0.450	0.456	0.462
31. VIII 21	0.479	0.466	0.480	0.491	0.451	0.464	0.480
1. IX 03	0.463	0.456	0.472	0.474	0.436	0.452	0.464

Table 4. Descending Atmospheric Radiation Fluxes at the 3 km level $G_3 \downarrow$ (cal/cm^2·min)

Date and time	Per nomograph of						
	Э	М	Ш	Б	Р	Я	Д
16. III 15	0.239	0.240	0.230	0.214	0.210	0.212	0.212
16. III 21	0.240	0.239	0.222	0.211	0.208	0.206	0.202
17. III 03	0.240	0.241	0.218	0.211	0.209	0.208	0.205
18. III 21	0.220	0.221	0.198	0.188	0.193	0.187	0.188
19. III 03	0.210	0.215	0.189	0.178	0.184	0.181	0.179
19. III 15	0.200	0.202	0.174	0.163	0.174	0.163	0.164
20. III 03	0.202	0.200	0.175	0.165	0.173	0.165	0.162
20. III 15	0.179	0.187	0.157	0.148	0.156	0.152	0.154
21. III 21	0.207	0.209	0.163	0.173	0.179	0.174	0.170
22. III 03	0.232	0.202	0.178	0.169	0.174	0.171	0.169
25. IV 03	0.227	0.228	0.202	0.195	0.200	0.192	0.191
25. IV 15	0.222	0.225	0.200	0.191	0.194	0.189	0.186
25. IV 21	0.241	0.239	0.230	0.212	0.211	0.205	0.204
11. V 07	0.233	0.231	0.216	0.202	0.208	0.198	0.198
15. V 07	0.298	0.292	0.300	0.278	0.288	0.285	0.288
30. V 21	0.279	0.279	0.267	0.259	0.350	0.341	0.342
31. V 03	0.265	0.264	0.248	0.239	0.238	0.231	0.232
28. VIII 03	0.296	0.296	0.278	0.275	0.288	0.289	0.280
28. VIII 15	0.291	0.290	0.294	0.278	0.279	0.287	0.281
28. VIII 21	0.331	0.325	0.322	0.321	0.302	0.309	0.303
31. VIII 15	0.326	0.324	0.317	0.318	0.305	0.299	0.300
31. VIII 21	0.342	0.327	0.327	0.324	0.315	0.306	0.305
1. IV 03	0.260	0.249	0.262	0.262	0.258	0.255	0.255

Table 5. Descending Atmospheric Radiation Fluxes of Atmosphere in Different Zones of the Globe and at Various Heights

G ↓ (cal/cm^2·min)

Latitude zone	Per nomograph of D	M	Ш	Б	P	Я	A
				z = 0 km			
0–10° N	0.567	0.543	0.571	0.577	0.525	0.542	0.56
10–20° N	0.530	0.511	0.537	0.541	0.502	0.515	0.52
20–30° N	0.498	0.474	0.504	0.496	0.467	0.480	0.4
30–40° N	0.428	0.412	0.425	0.427	0.396	0.408	0.41
40–50° N	0.368	0.356	0.364	0.363	0.339	0.349	0.35
50–60° N	0.311	0.303	0.301	0.297	0.279	0.290	0.28
60–70° N	0.255	0.256	0.241	0.238	0.223	0.234	0.2
				z = 3 km			
0–10° N	0.407	0.387	0.401	0.402	0.378	0.373	0.3
10–20° N	0.367	0.355	0.367	0.354	0.336	0.332	0.3
20–30° N	0.337	0.329	0.324	0.321	0.305	0.300	0.29
30–40° N	0.298	0.295	0.288	0.279	0.270	0.265	0.26
40–50° N	0.262	0.260	0.246	0.239	0.232	0.238	0.22
50–60° N	0.223	0.223	0.205	0.196	0.196	0.193	0.1
60–70° N	0.190	0.188	0.166	0.157	0.162	0.160	0.15
				z = 6 km			
0–10° N	0.192	0.186	0.162	0.153	0.168	0.147	0.14
10–20° N	0.157	0.153	0.119	0.115	0.136	0.117	0.11
20–30° N	0.144	0.129	0.101	0.088	0.121	0.104	0.09
30–40° N	0.119	0.110	0.076	0.073	0.089	0.082	0.07
40–50° N	0.109	0.088	0.066	0.053	0.083	0.071	0.05
50–60° N	0.094	0.082	0.049	0.048	0.076	0.080	0.0
60–70° N	0.094	0.085	0.051	0.049	0.076	0.059	0.0

Table 6. Ascending Radiation Fluxes at the 3 km level and on the Earth's Surface

G ↑ (cal/cm^2·min)

Date and time	Per nomograph of D	M	Ш	Б	P	Я	A	σT_0^4
				z = 3 km				z = 0
16. III 15	0.416	0.429	0.423	0.419	0.417	0.427	0.430	0.469
16. III 21	0.408	0.419	0.414	0.411	0.406	0.419	0.434	[illegible]
17. III 03	0.404	0.412	0.409	0.407	0.402	0.413	0.416	0.425
18. III 21	0.391	0.406	0.397	0.385	0.391	0.406	0.408	0.427
19. III 03	0.376	0.389	0.384	0.379	0.377	0.388	0.390	0.397
19. III 15	0.398	0.410	0.401	0.399	0.395	0.408	0.415	[illegible]
20. III 03	0.365	0.374	0.371	0.365	0.364	0.373	0.378	0.376
20. III 15	0.380	0.384	0.373	0.371	0.368	0.382	0.386	0.427
21. III 21	0.377	0.389	0.383	0.377	0.376	0.385	0.388	0.403
22. III 03	0.366	0.376	0.372	0.368	0.364	0.374	0.381	0.379
25. IV 03	0.419	0.432	0.434	0.423	0.418	0.430	0.438	0.446
25. IV 15	0.425	0.438	0.439	0.427	0.424	0.438	0.442	0.491
25. IV 21	0.436	0.440	0.432	0.430	0.426	0.436	0.441	0.471
11. V 07	0.430	0.441	0.433	0.428	0.429	0.443	0.449	0.481
15. V 07	0.462	[illegible]	0.464	0.461	0.460	0.473	0.489	0.509
30. V 21	0.461	0.472	0.464	0.463	0.457	0.470	0.479	0.496
31. V 06	0.464	0.474	0.475	0.462	0.457	0.470	0.478	0.501
28. VIII 08	[illegible]	0.509	0.503	0.500	0.494	0.508	0.510	0.536
29. VIII 15	[illegible]	0.526	0.510	0.515	0.512	0.527	0.530	0.600
29. VIII 21	0.594	0.511	0.503	0.501	0.496	0.513	0.515	0.598
31. VIII 15	0.532	0.545	0.536	0.534	0.531	0.544	0.546	0.596
31. VIII 21	0.530	0.589	0.527	0.522	0.522	0.534	0.536	0.560
1. IX 06	0.509	0.514	0.512	0.510	0.508	0.515	[illegible]	0.537

Table 7. Ascending Radiation Fluxes in Various Zones of Globe and at Various Heights G ↑ (cal/cm²·min)

Latitude zone	Per nomograph of							σT_0^4
	Э	М	Ш	Б	Р	Н	Д	
				z = 3 km				[illegible]
0—10° N	0.587	0.606	0.590	0.589	0.586	0.583	0.602	[illegible]
10—20° N	0.550	0.547	0.567	0.558	0.536	0.570	0.572	0.64
20—30° N	0.533	0.550	0.535	0.534	0.533	0.545	0.548	[illegible]
30—40° N	0.485	0.497	0.485	0.484	0.483	0.491	0.505	0.54
40—50° N	0.438	0.449	0.441	0.436	0.437	0.446	0.455	0.48
50—60° N	0.388	0.392	0.393	0.386	0.399	0.389	0.404	0.42
60—70° N	0.343	0.348	0.347	0.341	0.342	0.350	0.358	0.36
				z = 8 km				
0—10° N	0.487	0.488	0.482	0.480	0.464	0.486	0.501	
10—20° N	0.452	0.470	0.448	0.449	0.446	0.478	0.487	
20—30° N	0.433	0.451	0.434	0.428	0.430	0.403	0.470	
30—40° N	0.391	0.400	0.392	0.392	0.392	0.416	0.429	
40—50° N	0.354	0.365	0.357	0.356	0.362	0.377	0.389	
50—60° N	0.322	0.332	0.330	0.329	0.323	0.343	0.356	
60—70° N	0.296	0.305	0.304	0.302	0.298	0.310	0.322	

Table 8. Effective Radiation at the Earth's Surface F_0(cal/cm²·min)

Date and time	Per nomograph of						
	Э	М	Ш	Б	Р	Н	Д
16. III 15	0.109	0.120	0.115	0.116	0.137	0.136	0.126
16. III 21	0.095	0.108	0.100	0.100	0.126	0.111	0.111
17. III 03	0.086	0.092	0.090	0.091	0.115	0.100	0.096
18. III 21	0.107	0.120	0.117	0.120	0.129	0.130	0.138
19. III 03	0.099	0.106	0.107	0.109	0.128	0.114	0.118
19. III 15	0.146	0.149	0.162	0.166	0.173	0.172	0.175
20. III 03	0.095	0.096	0.108	0.107	0.124	0.113	0.112
20. III 15	0.131	0.138	0.144	0.148	0.150	0.155	0.156
21. III 21	0.106	0.114	0.119	0.121	0.137	0.127	0.130
22. III 06	0.090	0.094	0.100	0.102	0.130	0.105	0.112
25. IV 03	0.106	0.114	0.111	0.113	0.135	0.119	0.122
25. IV 15	0.141	0.154	0.156	0.153	0.160	0.167	0.161
25. IV 21	0.107	0.119	0.110	0.114	0.136	0.125	0.121
11. V 07	0.120	0.131	0.125	0.127	0.150	0.138	0.136
15. V 07	0.096	0.109	0.098	0.095	0.127	0.113	0.106
30. V 21	0.086	0.093	0.085	0.087	0.119	0.106	0.098
31. V 03	0.092	0.095	0.082	0.081	0.121	0.105	0.106
30. VIII 03	0.083	0.090	0.075	0.073	0.111	0.096	0.090
30. VIII 15	0.131	0.150	0.128	0.127	0.150	0.147	0.141
30. VIII 21	0.102	0.116	0.096	0.094	0.131	0.118	0.112
31. VIII 15	0.124	0.144	0.118	0.117	0.146	0.140	0.134
31. VIII 21	0.081	0.094	0.071	0.069	0.109	0.085	0.080
1. IX 03	0.074	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 9. Effective Radiation at the 3 km Level F_3 (cal/cm^2·min)

Date and time	Per nomograph of						
	Д	М	Ш	Б	Р	Я	Ж
16. III 15	0.177	0.180	0.203	0.205	0.207	0.215	0.218
16. III 21	0.168	0.180	0.192	0.200	0.198	0.213	0.222
17. III 03	0.164	0.171	0.191	0.196	0.193	0.205	0.213
18. III 21	0.171	0.186	0.190	0.207	0.201	0.219	0.220
19. III 03	0.160	0.174	0.186	0.201	0.193	0.207	0.211
19. III 15	0.198	0.208	0.227	0.236	0.231	0.245	0.251
20. III 03	0.163	0.174	0.196	0.200	0.191	0.208	0.216
20. III 15	0.190	0.197	0.216	0.223	0.212	0.230	0.234
21. III 21	0.170	0.180	0.200	0.204	0.197	0.212	0.218
22. III 03	0.164	0.174	0.194	0.197	0.190	0.203	0.212
25. IV 03	0.192	0.204	0.222	0.228	0.218	0.238	0.247
25. IV 15	0.203	0.214	0.229	0.236	0.230	0.249	0.256
25. IV 21	0.185	0.201	0.212	0.216	0.215	0.233	0.237
11. V 07	0.197	0.210	0.217	0.226	0.221	0.245	0.251
15. V 07	0.164	0.180	0.184	0.183	0.194	0.207	0.212
30. V 21	0.182	0.193	0.197	0.204	0.207	0.229	0.237
31. V 03	0.194	0.210	0.217	0.223	0.219	0.230	0.246
26. VIII 03	0.190	0.221	0.225	0.225	0.230	0.249	0.250
26. VIII 15	0.211	0.226	0.234	0.237	0.242	0.265	0.262
28. VIII 21	0.170	0.180	0.181	0.180	0.196	0.213	0.217
31. VIII 15	0.197	0.221	0.210	0.216	0.225	0.245	0.246
31. VIII 21	0.173	0.192	0.204	0.190	0.207	0.226	0.231
1. IX 03	0.149	0.166	0.166	0.153	0.178	0.193	0.195

Table 10. Effective Radiation in Various Zones of the Globe and at Various Heights F(cal/cm^2·min)

Latutude zone	Per nomograph of						
	Д	М	Ш	Б	Р	Я	Ж
			z = 0 km				
0–10° N	0.110	0.124	0.096	0.090	0.143	0.125	0.107
10–20° N	0.116	0.135	0.102	0.105	0.144	0.131	0.119
20–30° N	0.123	0.147	0.117	0.125	0.156	0.141	0.136
30–40° N	0.118	0.134	0.121	0.119	0.150	0.136	0.132
40–50° N	0.112	0.125	0.117	0.116	0.142	0.132	0.128
50–60° N	0.110	0.118	0.120	0.124	0.142	0.131	0.133
60–70° N	0.110	0.109	0.124	0.127	0.142	0.131	0.131
			z = 3 km				
0–10° N	0.180	0.218	0.189	0.187	0.204	0.225	0.235
10–20° N	0.192	0.219	0.200	0.204	0.220	0.236	0.246
20–30° N	0.196	0.221	0.211	0.213	0.228	0.245	0.254
30–40° N	0.186	0.202	0.199	0.205	0.213	0.229	0.241
40–50° N	0.176	0.180	0.195	0.190	0.205	0.218	0.229
50–60° N	0.168	0.169	0.188	0.193	0.194	0.206	0.218
60–70° N	0.150	0.159	0.181	0.184	0.180	0.190	0.204
			z = 8 km				
0–10° N	0.275	0.302	0.300	0.307	0.296	0.349	0.353
10–20° N	0.295	0.317	0.309	0.334	0.317	0.361	0.377
20–30° N	0.289	0.315	0.335	0.330	0.309	0.358	0.378
30–40° N	0.272	0.290	0.316	0.319	0.333	0.336	0.356
40–50° N	0.254	0.278	0.301	0.308	0.330	0.306	0.334
50–60° N	0.229	0.250	0.281	0.281	0.347	0.303	0.302
60–70° N	0.202	0.230	0.253	0.259	0.229	0.251	0.272

Fig. 2. Descending atmospheric radiation flux for various latitudinal zones per nomographs of: 1 — Elsasser; 2 — Mügge and Möller; 3 — Robinson; 4 — Brooks; 5 — Yamamoto; 6 — Shekhter; 7 — Dmitriyev.

The divergence of the results determined by the various nomographs is comparatively large. Especially great are the divergences of values of effective atmospheric radiation; descending radiation fluxes the divergence lies within the limits of measurement error.

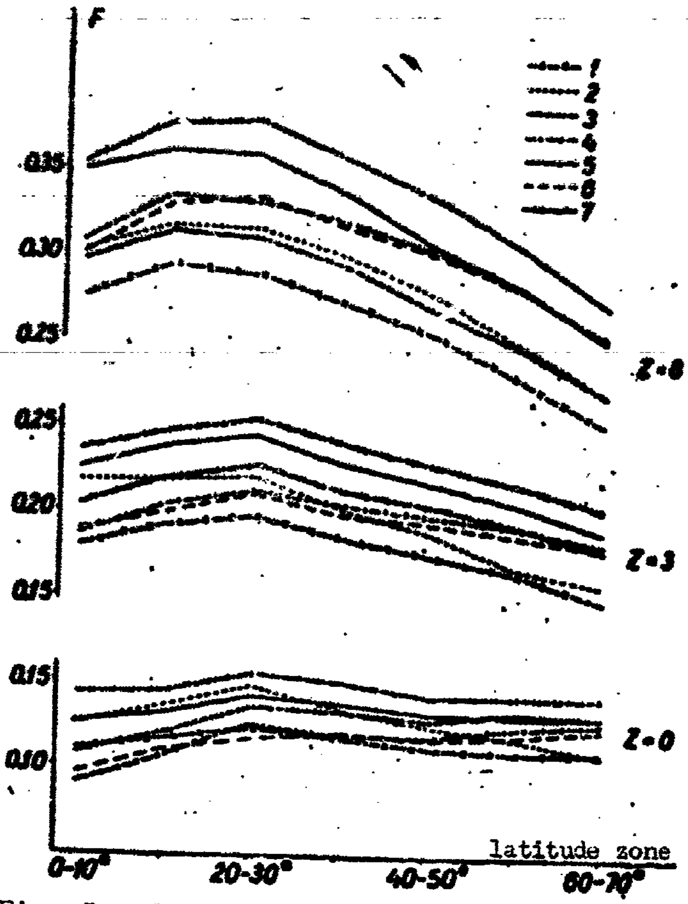

Fig. 3. Effective radiation for various latitude zones per nomographs of: 1 — Elsasser; 2 — Mügge and Möller; 3 — Robinson; 4 — Brooks; 5 — Yamamoto; 6 — Shekhter; 7 — Dmitriyev.

The divergence of the results increases with height. On the earth's surface in the region of effective absorbing masses $w \approx 1 - 1.5$ "cm" there is still very good agreement between the values of radiation fluxes of the atmosphere as determined by the various nomographs. There are exclusively great differences only when the effective absorbing masses $w > 2$ "cm" (up to 10% of the value of back radiation and up to 30% of the value of effective radiation). The maximum difference in this region constitutes 0.052 cal/cm^2·min. At a height of 3 km the curves of fluxes of thermal radiation noticeably differ and at 8 km the differences in the values of back radiation for one and the same sounding of the atmosphere attain as much as 23% ($0.053\ cal/cm^2 \cdot min$) and the differences in the values of effective radiation reach 24% ($0.089\ cal/cm^2 \cdot min$).

The overall picture of the values of atmospheric fluxes is very complex and the distinctions in the results seem nonsystematic, since corresponding curves intersect and their relative location changes with height. Good coincidence is found only in the results from the nomographs of Shekhter and Brooks. Comparatively satisfactory agreement is noted in the results from the nomographs of Yamamoto and Dmitriyev, but the differences in radiation fluxes here increase strongly with height. There is a certain coordination in the values of back radiation found by the nomographs of Elsasser and Möller. The remaining results do not coincide and the differences grow strongly with height.

Let us try to clarify the causes of these divergences. First of all we will compare the results of the determination of radiation fluxes (Figs. 2 and 3) and the corresponding transmission functions (Fig. 1). Actually a good correlation exists between the movement of the transmission functions and the values of fluxes of thermal radiation. Transmission functions of various nomographs cross at approximately those values of effective absorbing masses at which there is intersection of the curves of the corresponding fluxes of thermal atmospheric radiation.[1]

A certain deflection from this rule can be found only at large absorbing masses and temperatures (there where the absolute values of planimetry error can be great) and in results obtained at very low

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[1]We will note that by this method it is impossible to compare the results obtained by the nomographs of Yamamoto with the other results, since Yamamoto considers the influence of CO_2 on absorption of long-wave radiation by means of a special nomograph.

atmospheric temperatures. For the nomograph of Mügge and Möller this correlation is weak. But here one should note that the transmission function of the Mügge and Möller nomograph is given for a temperature of 313°K and the rest of the transmission functions are mostly for 273°K. With comparison of the transmission function per Mügge and Möller with the function of absorption per Elsasser for 313°K (Fig. 1) it is clear that quite good correlation exists between these transmission functions and the corresponding values of atmospheric back radiation.

Thus the transmission function is one of the main factors determining the values of radiation fluxes according to one or another nomograph.

Besides this, a certain influence is rendered on the determination of radiation fluxes on the nomographs by the fundamental construction of the nomographs, and mainly by the dependence of absorption on temperature. As is known, during calculation of the "effect of displacement" somewhat larger values of back radiation are obtained. This temperature effect emerges especially strongly at low atmospheric temperatures. On the basis of this it is possible to explain the relatively large values of back radiation from the nomographs of Dmitriyev, Yamamoto, Elsasser, and Mügge and Möller at low temperatures.

Since for the nomographs of Dmitriyev and Yamamoto the effective absorbing masses are calculated with use of the correction $\frac{p}{p_c}$ and in the other nomographs this correction is $\sqrt{\frac{p}{p_c}}$, we obtain corresponding effective absorbing masses, on the average, 10% smaller (with small absorbing masses, even up to 50%). This is one of the reasons for which the values of back radiation are smaller by the nomographs of Dmitriyev and Yamamoto than by other nomographs. To study the influence of the correction for pressure f(p) on atmospheric radiation fluxes, we produced additional calculations by the Yamamoto and Dmitriyev nomographs, using the correction $\sqrt{\frac{p}{p_c}}$, and by the Elsasser nomograph with account taken of the correction $\frac{p}{p_c}$. The results are given in Tables 11 and 12.

Table 11. Influence of Correction for Pressure on Descending Atmospheric Radiation Flux G ↓ (cal/cm²·min)

Nomographs	Yamamoto						Dmitriyev		Elsasser	
Latitude zone	z = 0 km		z = 3 km		z = 6 km		z = 0 km		z = 0 km	
	*	**	*	**	*	**	*	**	*	**
0–10° N	0.542	0.549	0.373	0.361	0.167	0.154	0.560	0.575	0.552	0.557
10–20° N	0.515	0.530	0.332	0.336	0.117	0.124	0.527	0.541	0.524	0.539
20–30° N	0.480	0.484	0.300	0.305	0.104	0.110	0.486	0.500	0.491	0.498
30–40° N	0.408	0.412	0.285	0.273	[illegible]	0.088	0.413	0.418	0.421	0.438
40–50° N	0.349	0.362	[illegible]	[illegible]	0.071	0.076	0.357	0.358	0.361	0.369
50–60° N	0.290	0.295	0.193	0.190	[illegible]	0.087	[illegible]	0.295	0.307	0.311
60–70° N	0.234	0.237	0.160	0.167	[illegible]	[illegible]	0.234	0.236	0.249	0.256

$^{*}\; w = \int e_w \frac{p}{p_c} dz$

$^{**}\; w = \int e_w \sqrt{\frac{p}{p_c}} dz$

Table 12. Influence of Correction for Pressure on Effective Atmospheric Radiation F(cal/cm²·min)

Nomographs	Yamamoto						Dmitriyev		Elsasser	
Latitude zone	z = 0 km		z = 3 km		z = 6 km		z = 0 km		z = 0 km	
	*	**	*	**	*	**	*	**	*	**
0–10° N	0.125	0.118	0.225	0.217	[illegible]	0.234	0.107	[illegible]	0.115	0.110
10–20° N	0.131	0.126	[illegible]	0.231	0.261	0.240	0.119	0.105	0.122	0.116
20–30° N	0.141	0.137	0.245	[illegible]	[illegible]	0.347	0.125	0.121	0.130	0.123
30–40° N	0.136	0.134	[illegible]	0.221	[illegible]	0.305	[illegible]	0.128	0.125	0.118
40–50° N	0.132	0.129	0.216	[illegible]	[illegible]	0.297	[illegible]	0.123	0.120	0.112
50–60° N	0.131	0.128	[illegible]	[illegible]	[illegible]	0.272	[illegible]	0.126	0.114	0.110
60–70° N	0.126	0.125	0.190	[illegible]	0.251	[illegible]	[illegible]	0.127	0.116	0.110

$^{*}\; w = \int e_w \frac{p}{p_c} dz$

$^{**}\; w = \int e_w \sqrt{\frac{p}{p_c}} dz$

As can be seen from the tables, the individual differences in back radiation are within the limits 0.003-0.015 cal/cm^2·min. The change in effective radiation is approximately the same. By the Yamamoto nomograph the changes in the values of back radiation constitute, on the average, 1.5% at $z = 0$, 2.6% at $z = 3$, and 7.6% at $z = 8$. The changes in the values of effective radiation are 3.1, 3.5, and 3.6%, respectively.

In order to recognize which meteoelement has an especially strong influence on radiation fluxes of the atmosphere, we studied the correlations between $G_0 \downarrow$ and t_0, $G_0 \downarrow$ and $w_{0,\infty}$, $G_3 \downarrow$ and t_3, $G_3 \downarrow$ and t_0, $G_3 \downarrow$ and $w_{3,\infty}$. These correlations were considered also for effective radiation.[1]

It was found that atmospheric back radiation gives quite good correlation both with temperature and also with the total content of water vapor. Typical pictures of this correlation are given in Figs. 4 and 5, where its values as computed by the Elsasser nomograph and also by other nomographs give an analogous picture.

Effective atmospheric radiation gives no correlation with temperature and effective absorbing mass.

The empirical formulas of Angstrom and Brent for the determination of effective radiation and back radiation of the atmosphere are widely known. With a cloudless sky they have the following general form:

$$\left.\begin{array}{l} \dfrac{F_0}{\sigma T_0^4} = f'(e_0), \\ \dfrac{G_0 \downarrow}{\sigma T_0^4} = f''(e_0). \end{array}\right\} \qquad (30)$$

where f' and f'' are certain functions of e_0.

[1]Here the index shows the height . above the earth's surface.

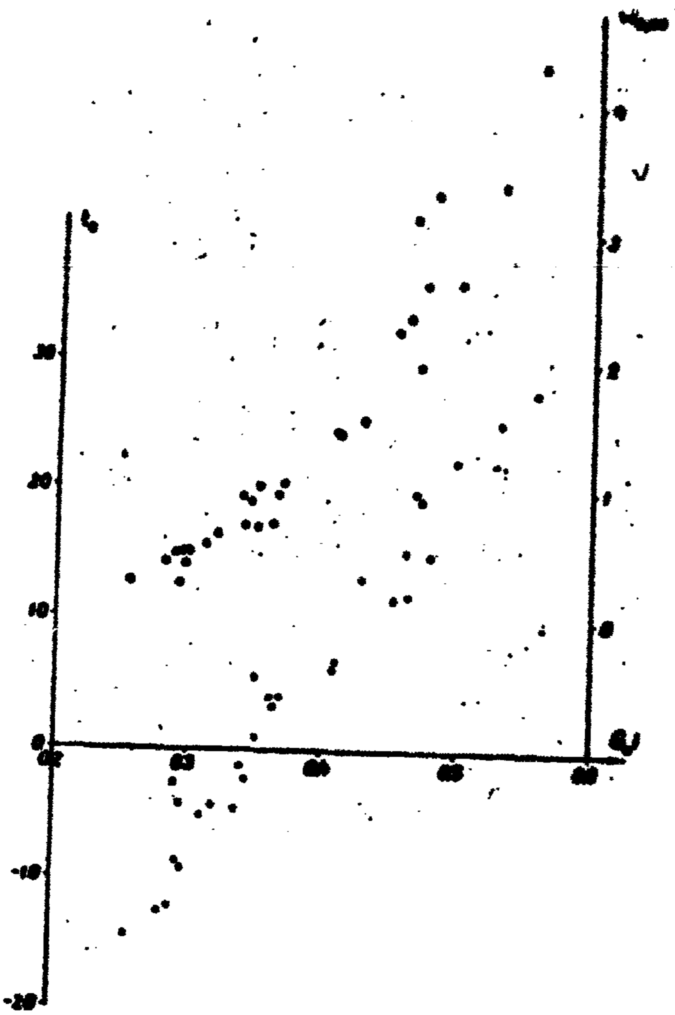

Fig. 4. ● — correlation between atmospheric back radiation and temperature on the earth's surface; ○ — correlation between atmospheric back radiation and the total content of water vapor on the earth's surface.

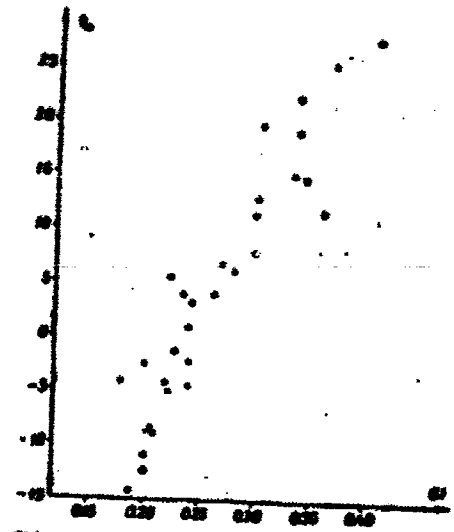

Fig. 5. Correlation between atmospheric back radiation at the 3 km level and the temperature on the earth's surface.

In order to check the validity of these formulas, in this work we studied the correlation between $\frac{F_0}{\sigma T_0^4}$ and e_0 and also that between $\frac{G_0 \downarrow}{\sigma T_0^4}$ and e_0, on the basis of values of F_0 and $G_0 \downarrow$ obtained by the nomographs.[1] Typical correlation graphs are depicted in Fig. 6.

As can be seen, there actually exists a certain correlation between the ratios $\frac{F_0}{\sigma T_0^4}$ and $\frac{G_0 \downarrow}{\sigma T_0^4}$ and the tension of water vapor e_0, but the

[1]It is necessary to note that in this case all the nomographs give approximately identical correlation graphs.

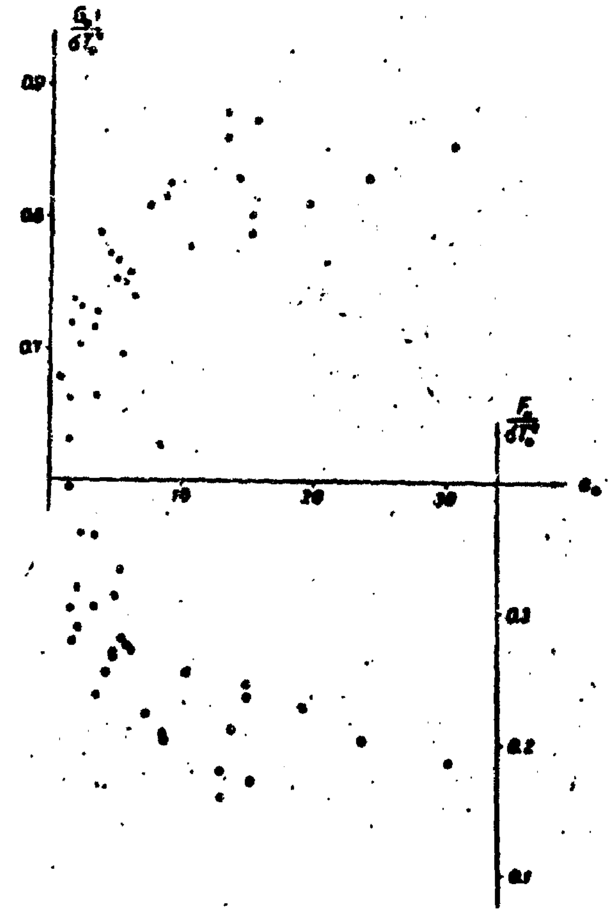

Fig. 6. ● — correlation between $\frac{G_0}{\sigma T_0^4}$ and water vapor tension on the earth's surface; ○ — correlation betwee. $\frac{F_0}{\sigma T_0^4}$ and water vapor tension on the earth's surface.

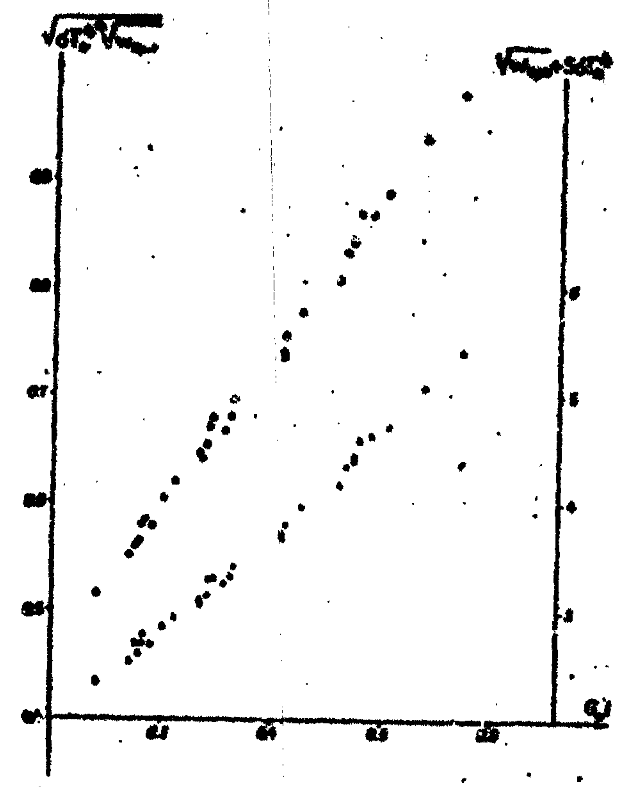

Fig. 7. ● — correlation between $\sqrt{w} + \delta\sigma T_0^4$ and the back radiation of the atmosphere on the earth's surface;

○ — correlation between $\sqrt{\sigma T_0^4 \sqrt{w}}$ and the back radiation of the atmosphere on the earth's surface.

spread of points is great. Therefore it is possible to think that empirical formulas of the type of (30) are useful only for tentative calculations.

Since in reality there is a simultaneous influence of temperature and water vapor on fluxes of thermal atmospheric radiation, it is natural to assume that a good correlation exists between fluxes and a certain function of T and $w_{z,\infty}$. As an example we studied the correlations between $G_0 \downarrow$ and $\sqrt{w_{0,\infty}} + a\sigma T_0^4$ (a is a certain constant) and also between $G_0 \downarrow$ and $\sqrt{\sigma T_0^4 \sqrt{w_{0,\infty}}}$. The correlation graph is shown in Fig. 7. Correlations are actually very good. Here all the nomographs give an approximately identical correlation. On the basis of these correlations it is possible to give empirical formulas, but for exact determination of the corresponding coefficients it is necessary to determine the radiation fluxes more exactly, which is impossible to do with the help of radiation nomographs. It is necessary to note that these correlations have no physical meaning. No correlation is observed for effective radiation.

We tried also to clarify how the influences of stratification is reflected in the results of the calculations. We compared the differences between the values of radiation fluxes according to the various nomographs for cases of inversion and without it. No correlation was found between these differences and inversions, so that all nomographs consider thermal stratification of the atmosphere to an approximately equal degree.

Appraisal of Nomographs

On the basis of the calculations in this work it is not so easy to resolve the question of which of the nomographs is the best. First of all, we do not have at our disposal data of measurement of radiation fluxes during sounding and therefore it is difficult to say which of the nomographs gives results closest to reality. Secondly, errors in planimetry are quite large (up to 10%) and factors weakly affecting the magnitudes of long-wave radiation are impossible to detect. It is difficult to determine, for instance, to what measure the influence of the various principles of construction of nomographs on radiation fluxes is expressed. Nonetheless, by working partially from the data of construction of the nomographs and on results obtained in our work it is possible to conduct a certain analysis of the quality of the radiation nomographs.

As was already noted, from the point of view of the principles involved the Dmitriyev nomograph is one of the best. Nonetheless it has certain essential deficiencies. First, the data on absorption of thermal radiation in atmosphere which lie at the basis of the construction of the Dmitriyev nomograph at present should be considered obsolete. The influence of carbon dioxide on the absorption of thermal radiation is quite ignored in this nomograph. Besides this, in constructing the isolines of temperature for the nomograph Dmitriyev calculated only six points for each line. But since the ordinate of these lines is a nonmonotonic function of the abscissa, the broken curves thus obtained only very approximately depict the real course of the isolines of temperature. For practical purposes the procedure of calculating radiation fluxes from three nomographs is complex and the planimetry error can be very considerable.

The main deficiency of the Elsasser and Robinson nomographs is the rough calculation of the radiation of carbon dioxide. These nomographs are useful only for surface calculations. Besides this, the generalized coefficient of absorption l_λ on the basis of which Elsasser constructed the transmission function of his nomograph was determined very inaccurately [1]. Regarding the function of absorption constructed by Robinson, a whole series of deficiencies exists in its determination also [14].

The nomograph of Mügge and Möller was built somewhat more successfully, since from the practical point of view it has unconditional advantages over the Dmitriyev nomograph. The influence of carbon dioxide is considered in dependence upon the content of carbon dioxide. But also these authors also use average, very approximate data about the absorption of long-wave radiation in the atmosphere [1].

In the Yamamoto nomograph the influence of carbon dioxide on absorption of radiation is considered most exactly. The appraisal of the influence of temperature on the function of absorption is also more correctly conducted.

The nomographs of Shekhter and Brooks are very useful from a practical point of view, since the isolines of temperature and absorbing mass here are straight lines. Besides this, the absorption functions of these nomographs, as compared to those of the nomographs of the other authors, are more reliable. It is interesting that the absorption functions per Shekhter and per Brooks are very close, despite the fact that they are determined by different methods and on the basis of different data. It is necessary to note that in the light of the most recent data [16, 15] the influence of carbon dioxide on atmospheric absorption is somewhat overvalued in the Shekhter nomograph.

The above-mentioned characteristic features are reflected in the results calculated by the various nomographs. It is possible to say that when conducting calculations by the nomographs of Dmitriyev, Elsasser, and also Mügge and Möller one obtains more or less reliable results only near the earth's surface, while the values for radiation fluxes at heights of 3 and 8 km are already noticeably inaccurate. The results from the Robinson nomographs are inadequate even at the surface of the earth.

Houghton and Brewer [17], experimentally determining fluxes of long-wave atmospheric radiation in the lower part of the troposphere, found that the Elsasser nomograph $\left(\text{correction } \frac{p}{p_c}\right)$ gives good agreement with observations and noticeably poorer coincidences are obtained on the basis of the nomographs of Yamamoto and Robinson.

Comparison of the results from the Elsasser nomograph $\left(\text{with the correction for pressure } \frac{p}{p_c}\right)$ with the corresponding values from the nomographs of Shekhter and Brooks obtained in this work, shows satisfactory agreement with the exception of extremely large values of back radiation in the zone 0-10°N. With these values the values of back radiation found from the Yamamoto coincide to a certain degree with these values with a correction for pressure of $\sqrt{\frac{p}{p_c}}$ (Table 13).

Table 13. Atmospheric Back Radiation of the Level of the Earth's Surface $G_0 \downarrow$ (cal/cm^2·min)

Latitude zone	Per nomograph of			
	Ш**	Б**	Э*	Я**
0—10° N	0.571	0.577	0.552	0.549
10—20° N	0.537	0.541	0.524	0.520
20—30° N	0.504	0.496	0.491	0.484
30—40° N	0.435	0.437	0.421	0.412
40—50° N	0.364	0.363	0.361	0.352
50—60° N	0.301	0.297	0.297	0.293
60—70° N	0.241	0.238	0.240	0.237

$$^{*}\ w = \int \rho_w \frac{p}{p_c} dz$$

$$^{**}\ w = \int \rho_w \sqrt{\frac{p}{p_c}} dz$$

Shlyakov [18], comparing the results of calculations of thermal radiation fluxes in the atmosphere by the Shekhter nomograph with the results of measurements, notes good agreement between them.

Thus it is possible to say that the most reliable results for various heights of troposphere are given by the nomographs of Shekhter and Brooks and also by the nomograph of Yamamoto. The results obtained with the Yamamoto nomograph sometimes differ quite noticeably in comparison with the results of the Shekhter and Brooks nomographs. This occurs mainly because of the use of different characteristics of absorption of water vapor. Clarification of which function of absorption is the most true requires special investigation.

It seems to us that first of all it is necessary to study in detail the quantitative characteristics of absorption of long-wave radiation in the atmosphere on the basis of the latest data, in order to obtain the most exact transmission function possible. Besides this it is necessary to clarify how to consider the influence of pressure on fluxes of thermal atmospheric radiation. As can be seen from Tables 11 and 12, the influence on the correction for pressure has value especially with small radiation fluxes. Gergen [19] affirms that the use of a correction for pressure during calculation of effective absorbing masses leads to results which are incorrect in principle, since in reality the absorption function depends on pressure. But from the practical point of view the use of effective absorbing mass is a unique method for simplification of calculations; direct introduction of the correction for pressure into the function of absorption would lead to extreme complication of radiation nomographs. Thus it should be determined whether the difference in the results of fluxes of thermal radiation arises with the introduction of corrections for pressure directly irto the function of absorption or with use of effective absorbing mass.

Another question is, what is the form of the correction itself? As we have already seen, there exists a series of formulas (7, 9, 10) and opinions relative to this correction. On the basis of some recent works [15, 16] one should apparently consider the real correction to have the form

$$f(p) = \left(\frac{p}{p_0}\right)^n. \qquad (31)$$

where $\frac{1}{2} \leq n \leq 1$.

The exact value of n requires more detailed investigation.

It was already noted that the influence of temperature on the function of absorption appears in two forms ("effect of displacement" and dependence of the coefficient of absorption from temperature). As is known, these factors act in opposite directions.

Certain authors [2, 11] consider that these factors approximately compensate one another. It follows from this that in no case is it possible to consider only one of these factors. This is the essential fundamental deficiency of the nomographs of Dmitriyev, Elsasser, and also Mügge and Möller, since in them only the "effect of diaplacement" was considered. Apparently so long as the data on the dependence of the coefficient of absorption on temperature are insufficient it is better to consider the function of absorption to be independent of temperature.

A more precise definition of the principles of radiation nomographs on the one hand permits determining the value of fluxes of thermal radiation more exactly, but on the other hand leads to complications. Due to this the planimetry errors which appear can exceed the obtained increase in accuracy. It seems that improvement of radiation nomographs by means of more exact calculation of the influence of the various additional factors is of value so long as this does not lead to essential complication of the nomograph.

Course of Thermal Fluxes of the Atmsophere on Different Latitudes and Heights in the Troposphere

Proceeding from the given reasoning, we decided to use mean values calculated by the nomographs of Shekhter and Brooks during the study of the movement of fluxes of thermal radiation in the troposphere with height for different latitudes. For a more detailed study of the movement of fluxes of thermal radiation with height we produced additional calculations by the nomographs of Shekhter and Brooks for heights of 2 and 5 km. The results are given in Table 14. On the basis of this table we calculated the mean values of fluxes of thermal atmospheric radiation (Table 15, Figs. 8 and 9).

Table 14. Movement of Thermal Fluxes of Atmospheric Radiation with Height for Different Latitudes

Latitude zone	Shekhter nomograph $G\downarrow$ (cal/cm²·min)					Brooks nomograph $G\downarrow$ (cal/cm²·min)				
	$z = 0$	$z = 2$	$z = 3$	$z = 5$	$z = 8$ km	$z = 0$	$z = 2$	$z = 3$	$z = 5$	$z = 8$ km
	Descending flux of atmospheric radiation									
0–10° N	0.571	[illegible]	[illegible]	[illegible]	[illegible]	0.577	[illegible]	0.402	[illegible]	[illegible]
10–20° N	0.537	[illegible]	0.357	[illegible]	0.119	0.541	0.424	0.354	0.254	0.115
20–30° N	0.504	[illegible]	0.304	0.231	0.101	[illegible]	0.378	0.321	[illegible]	[illegible]
30–40° N	[illegible]	0.344	[illegible]	[illegible]	0.076	0.427	0.341	0.279	0.194	0.073
40–50° N	[illegible]	[illegible]	[illegible]	0.154	[illegible]	0.363	0.291	[illegible]	0.144	0.053
50–60° N	[illegible]	[illegible]	[illegible]	0.125	[illegible]	[illegible]	[illegible]	0.195	0.120	[illegible]
60–70° N	[illegible]	[illegible]	[illegible]	[illegible]	0.051	[illegible]	0.181	0.157	0.102	[illegible]
	Effective atmospheric radiation									
	F (cal/cm²·min)					F (cal/cm²·min)				
0–10° N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.141	[illegible]	[illegible]	[illegible]
10–20° N	[illegible]	[illegible]	[illegible]	0.245	[illegible]	0.105	[illegible]	0.204	0.245	0.334
20–30° N	0.117	[illegible]	0.211	0.256	[illegible]	[illegible]	0.192	0.213	[illegible]	[illegible]
30–40° N	[illegible]	[illegible]	[illegible]	0.242	0.316	0.119	[illegible]	[illegible]	[illegible]	0.319
40–50° N	0.117	0.104	[illegible]	0.241	[illegible]	[illegible]	0.167	[illegible]	[illegible]	[illegible]
50–60° N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.134	[illegible]	[illegible]	[illegible]	0.261
60–70° N	[illegible]	[illegible]	[illegible]	0.215	[illegible]	0.127	[illegible]	0.104	0.221	[illegible]

As can be seen from these results, atmospheric back radiation decreases from the equator to the north pole at all heights. Here at the level of the earth's surface this decrease is somewhat less in the tropic and subtropic zones than in the middle latitudes. In middle

Table 15. Mean Values of Thermal Fluxes of the Atmosp' re for Different Latitudes and Heights

Latitude zone	z = 0	z = 2	z = 3	z = 5	z = 8 km	z = 0	z = 2	z = 3	z = 5	z = 8 km
	G↓ (cal/cm²·min)					F (cal/cm²·min)				
0–10°N	0.374	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10–20°N	[illegible]	[illegible]	[illegible]	0.257	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20–30°N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
30–40°N	[illegible]	[illegible]	[illegible]	[illegible]	0.074	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
40–50°N	[illegible]	[illegible]	[illegible]	0.140	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
50–60°N	[illegible]	[illegible]	[illegible]	0.122	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
60–70°N	[illegible]	[illegible]	[illegible]	0.104	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

of the troposphere this decrease occurs more or less linearly; at a height of 8 km from the equator to 40°N there occurs a comparatively fast decrease, but in the zone 40-70°N the value of back radiation is practically unchanged.

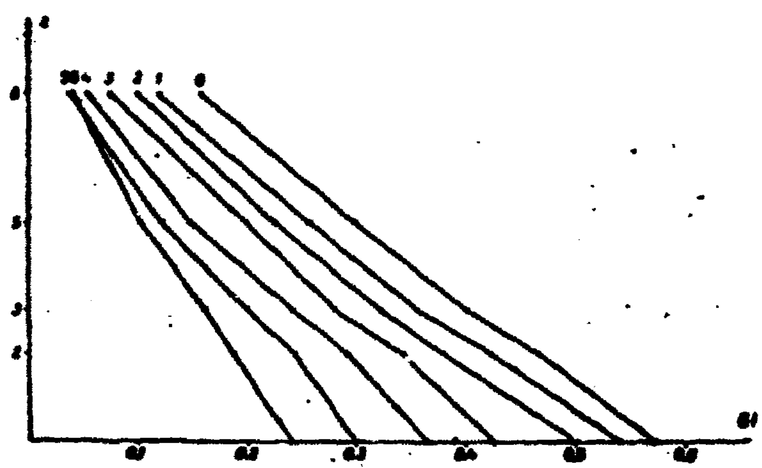

Fig. 8. Movement of back radiation of the atmosphere with height: 0 — 0-10°N; 1 — 10-20°N; 2 — 20-30°N; 3 — 30-40°N; 4 — 40-50°N; 5 — 50-60°N; 6 — 60-70°N.

Effective radiation has a sharply expressed maximum in the zone 20-30°N, which with an increase in height is displaced nearer to the zone 10-20°N. The cause of this maximum is apparently the comparatively large values of temperature and small values of humidity in the subtropical regions. At the level of the earth's surface the greatest values of effective radiation are obtained in the zones 50-60°N and 60-70°N. It is possible to consider that these values are explained by the low humidity of these latitudes on clear March days, when the temperature of earth's surface at the same time is relatively high.

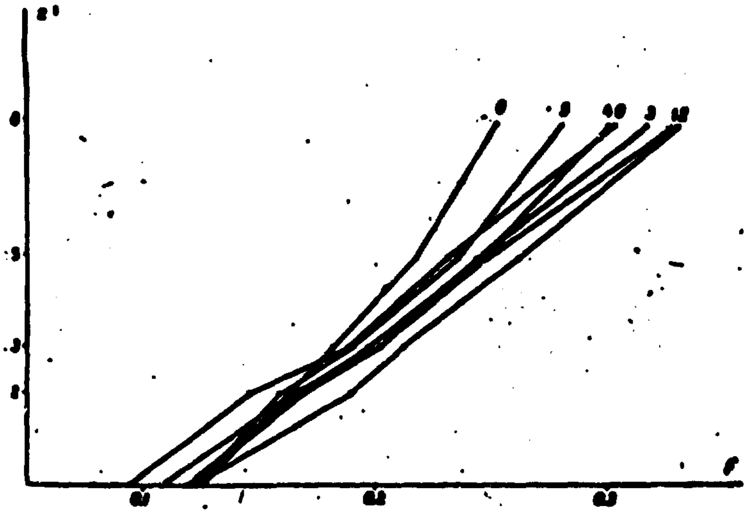

Fig. 9. Movement of effective radiation with height: 0 – 0-10°N; 1 – 10-20°N; 2 – 20-30°N; 3 – 30-40°N; 4 – 40-50°N; 5 – 50-60°N; 6 – 60-70°N.

On all remaining heights in the troposphere there is a decrease in effective radiation from the zone 20-30°N to the pole.

Figures 8 and 9 show the movement of back radiation and effective atmospheric radiation with height. Within the limits 0-8 km thermal fluxes of the atmosphere change more or less linearly. Table 16 gives the corresponding gradients of the change in back radiation and effective radiation at various high-altitude regions.

Table 16. Average Gradients of Atmospheric Thermal Fluxes for Different Latitudes and Heights

Latitude zone	$\Delta G\downarrow/\Delta z$ (cal/cm^2·min·km)				$\Delta F/\Delta z$ (cal/cm^2·min·km)			
	0–2 km	2–3 km	3–5 km	5–8 km	0–2 km	2–3 km	3–5 km	5–8 km
0–10° N	–0.053	–0.066	–0.062	–0.047	0.026	0.042	0.022	0.024
10–20° N	–0.058	–0.068	–0.060	–0.046	0.028	0.038	0.023	0.028
20–30° N	–0.060	–0.058	–0.061	–0.040	0.034	0.023	0.025	0.023
30–40° N	–0.042	–0.060	–0.041	–0.042	0.024	0.033	0.021	0.025
40–50° N	–0.036	–0.050	–0.046	–0.032	0.024	0.031	0.024	0.019
50–60° N	–0.028	–0.044	–0.039	–0.025	0.018	0.031	0.023	0.015
60–70° N	–0.026	–0.026	–0.029	–0.018	0.019	0.019	0.016	0.012

In conclusion, I express my deep gratitude to Professor K. Ya. Kondrat'yev for his valuable counsel and attention to my work.

Designations and Corresponding Units Used in this Article

Designations	Units	Meaning
1	2	3
A	—	Absorption function for parallel radiation.
A_D	—	Absorption function for diffuse radiation.
$B = \pi E = \sigma T^4$	$\frac{cal}{cm^2 \cdot min}$	Radiation flux of an ideal black body.
E_λ	$\frac{cal}{cm^2 \cdot min \cdot ster}$	Intensity of radiation of an ideal black body at wavelength λ.
$E = \int_0^\infty E_\lambda d\lambda$	"	Integral intensity of radiation of an ideal black body.
e	mb	Tension of water vapor.
$F = G\uparrow - G\downarrow$	$\frac{cal}{cm^2 \cdot min}$	Effective atmospheric radiation.
f_λ	—	Fraction of total radiation of an ideal black body corresponding to wavelength λ.
$G\downarrow$	$\frac{cal}{cm^2 \cdot min}$	Descending atmospheric radiation flux.
$G\uparrow$	"	Ascending flux of radiation of the atmosphere and the earth.
$H_n(x)$	—	Gold function
$I\downarrow$	$\frac{cal}{cm^2 \cdot min \cdot ster}$	Intensity of descending radiation flux.
$I\uparrow$	"	Intensity of ascending radiation flux.
k_λ	1/"cm"	Coefficient[1] of absorption at wavelength λ.
l_λ	1/"cm"	Generalized coefficient of absorption at wavelength λ.
m	"cm"	Mass of substance absorbing radiation.
m^1	"cm"	Effective mass of absorbing substance.
P	—	Transmission function for parallel radiation.

Table (Continued)

Designations	Units	Meaning
1	2	3
P_D	–	Transmission function for diffuse radiation.
p	mb	Air pressure.
q	g/kg	Specific humidity.
T	$^{\circ}K$	Absolute temperature.
t	$^{\circ}C$	Temperature.
u	"cm"	Effective absorbing mass of carbon dioxide in the atmosphere.
w	"cm"	Effective absorbing mass of water vapor in the atmosphere.
$w_{z,\infty}$	"cm"	Total content of water vapor in the atmosphere, counting from level z.
z	km	Height above the earth's surface.
δ	1/cm	Half-width.
ϑ	deg	Zenith angle.
ε		Emittance.
λ	μ	Wavelength.
ν	1/cm	Wave number.
ρ_m	g/cm^3	Density of substance absorbing radiation.
ρ_w	g/cm^3	Density of water vapor in atmosphere.
$\sigma = 0{,}814 \cdot 10^{-10}$	$\frac{cal}{cm^2 \cdot min \cdot ster}$	Stefan-Boltzmann constant.
Б	–	Per Brooks nomograph.
Д	–	Per Dmitriyev nomograph.
М	–	Per Mügge and Möller nomograph.
Р	–	Per Robinson nomograph.
Ш	–	Per Shekhter nomograph.
Э	–	Per Elsasser nomograph.
Я	–	Per Yamamoto nomograph.

[1]"cm" in centimeters of precipitated substance at STP.

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