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Translation of

Nekotorye radiatsionnye kharakteristiki v tumane

by

I. V. Koshelenko

Kiev. Ukrainskii Nauchno-Issledovatel'skii Gidrometeorologicheskii Institut, Trudy, No. 47: 22-29, 1965.

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SOME CHARACTERISTICS OF RADIATION IN FOG

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I. V. Koshelenko

Data are presented on the radiation balance and total radiation in fog at ground level, at the top of the fog layer, and within the fog. The mean attenuation factors of long-wave and short-wave radiation in a fog layer are calculated on the basis of these data.

The importance of long-wave and short-wave radiation for fog formation has been demonstrated in a number of papers [2, 3, 5]. The present paper is a continuation of this work and is based on the data of actinometric observations at Bagrinova Gora (Kiev) in 1958-1962 and special aircraft flights to study fog in 1960-1962. N. I. Goisa was in charge of equipping the aircraft with the actinometric instruments and supervized the observations.

Radiational heating of the ground is generally responsible for fog dispersal or the transformation of fog into low clouds during the daylight hours [5]. In this respect, it is interesting that fog dispersal begins with the appearance of small, isolated inhomogeneities. This process is evident from an aircraft 200 to 500 m above the fog; individual condensations begin to appear above a relatively level fog layer. The fog appears to be transforming into stratocumulus clouds. Gradually the gaps between the condensations become larger and the whole layer rises. Then breaks appear in the layer and become larger with time, and finally, only broken patches of clouds remain.

The fog thickens from below as it changes into low clouds which persist for a long time. Therefore, the local fluctuations of many meteorological elements in the fog (humidity, liquid-water content, visibility, et al.) increase considerably before and during fog dispersal, and must be taken into account when studying the fluctuations of the various fog elements. This is apparent on strip charts of transparency, where the scatter of points of the visibility record increases substantially before fog dispersal.

Both fog and clouds considerably attenuate the radiation passing through them. Table 1 shows the mean radiation balance of the ground, and the scattered radiation in fog and in clear weather as a function of the solar elevation. Table 1 and an analysis of individual cases show that during the night, when there is no solar radiation, the radiation balance at the ground is usually negative in fog, but its absolute values are low (~0. 02 to 0. 05 cal/cm^2 min). The radiation balance at the ground in fog was zero in 25% of the cases, and was positive only during considerable temperature inversions in the fog layer, when the temperature of the fog layer was much higher than that of the ground and the fog was more than 200 to 300 m thick. These instances are very rare, however, since the temperature variation in fog is small.

Table 1

Radiation Balance and Scattered Radiation Values at Ground Level in Fog and in Clear Weather (cal/cm^2 min)

Characteristic	Night	Solar elevation in degrees									No. of cases
		0	5	10	15	20	25	30	35	40	
Radiation balance in fog, no snow cover	-0,02	-0,02	-0,01	0,00	0,04	0,07	0,10	0,12	0,12	0,13	40
Radiation balance in fog, snow cover	-0,04	-0,04	-0,02	-0,02	0,01	0,03	0,06	0,07	—	—	15
Scattered radiation, in fog		0,00	0,02	0,06	0,09	0,12	0,14	0,16	0,16	0,17	76
Scattered radiation, clear sky		0,01	0,06	0,08	0,10	0,10	0,11	0,12	0,13	0,14	81

The radiation balance becomes positive in the daytime in the absence of a snow cover at a solar elevation of 5 to 8°, i. e., about 1 to 1 1/2 hours after sunrise; it reaches 0. 05 to 0. 12 cal/cm^2 min during the hours around noon. In the presence of a snow cover the radiation balance is usually close to zero, becoming positive and reaching 0.02 to 0.06 cal/cm^2 min only during the hours close to noon.

In winter, the radiation balance is negative during the noon hours as well, when the albedo reaches 80 to 85% for fresh snow. These findings are in good agreement with the diurnal behavior of fog. Fogs generally disperse during the day if there is no snow cover, but disperse far less often if there is one.

Table 1 shows that the scattered radiation at low solar elevations is smaller in fog than in clear weather, but at high solar elevations, the pressure of the scattered radiation is greater in fog than in clear weather.

Some erroneous conclusions in [7] regarding the radiation balance in fog must be pointed out in connection with these findings. Figures 6 and 9 in [7] show the diurnal radiation balance pattern and the heights of the temperature inversion, from which it is apparent that the maximum negative radiation balance values (-0.3 and -0.4 cal/cm^2 min) were observed at noon, while the night figures were -0.08 and -0.10 cal/cm^2 min. Such large negative radiation balance values are completely impossible at ground level under the most favorable conditions, let alone in winter. The effective radiation produces a negative radiation balance which does not exceed 0.18 to 0.20 cal/cm^2 min even in summer, but solar radiation will always produce a positive radiation balance.

Figure 6 of [7] shows a distinct diurnal temperature pattern which can be produced only by a positive radiation balance, inasmuch as the synoptic situation remained unchanged. If the inversion is disturbed by an increase in wind speed, the temperature at the shelter level will also increase, but this is not related to the diurnal pattern. The mean data for Moscow show a total solar radiation pressure in January of 0.3 to 0.4 cal/cm^2 min, while the albedo of the snow is 50 to 60%, making the radiation balance +0.12 cal/cm^2 min. This value is in good agreement with the temperature rise in Fig. 6 of [7]. After sunrise, when the radiation balance increases, the temperature rise may begin before the balance becomes positive, but the radiation balance <u>must</u> increase.

There are cases where the radiation balance is slightly negative, but the temperature is rising slightly; this can happen after sunrise or even in the middle of the day. In these rare instances there is relatively clean snow with a high albedo directly below the balance meter, while the surrounding region has a considerably lower integral albedo, owing to the presence of various objects, vegetation, etc. A positive radiation balance therefore results from the integral albedo. At Kiev, for a solar elevation of 20° (corresponding to midday in January) the radiation balance in clear weather with no snow is 0.25 cal/cm^2 min; it is 0.10 cal/cm^2 min for old snow, and 0.04 cal/cm^2 min for fresh snow.

Perhaps the author of [7] made a direct reading of the balance meter, which records the balance without direct solar radiation. However, the direct solar radiation must then be added to obtain the total balance. From the erroneous data in figs. 6 and 9, the author of [7] has drawn erroneous conclusions: "The disruption of surface inversions during the day and their formation at night makes the diurnal pattern of the radiation balance above a snow cover the <u>reverse</u> of the diurnal pattern of solar radiation and air temperature in the layer of air near the ground until the middle of March ... The absolute value of the negative radiation balance in the case of surface inversion is usually several factors smaller than after its disruption ..."

There are still other errors in [7]: for example, the assertion that the radiation balance in winter above a snow cover is negative both day and night, which is true only in northern latitudes. In Moscow at noon, it can be negative only for fresh snow. As a rule, the radiation balance is positive at noon for old snow in clear weather.

A link was established in [5] between the fog thickness and the pressure of the scattered radiation. Table 2 shows the radiation balance and scattered radiation <u>versus</u> fog intensity.

Table 2

Radiation Balance and Scattered Radiation (cal/cm^2 min) <u>versus</u> Fog Intensity

	Visibility Range, m			Number of cases
	50-200	200-500	500-1000	
Radiation balance at night	-0.02	-0.03	-0.02	24
Radiation balance at 1230 LMT	0.08	0.10	0.09	31
Scattered radiation at 1230 LMT	0.11	0.13	0.14	38

It is clear from table 2 that only scattered radiation increases slightly at noon when the fog thins. The radiation balance is practically independent of fog intensity both day and night, with the exception of a slight increase at night accompanying fog intensification. This lack of correlation apparently can be explained as follows: fog intensity was measured only at ground level, although it usually varies considerably with height. The slight increase of effective radiation at night accompanying fog intensification can be explained as follows: intense fog is observed, on the average, with stronger temperature and humidity inversions, resulting in an increase of atmospheric counter-radiation.

In what follows, it will be shown that a fog with a liquid-water content of 0.2 g/m^3 and a thickness of more than 200 m absorbs practically all the radiation and consequently radiates like an absolutely black body. When such a fog exists, its downward radiation is $E_f = \sigma T_f^4$, while the radiation from the ground is $E_g = \sigma T_g^4$, whence the effective radiation F can be obtained by the formula

$$F = E_g - E_f = \sigma T_g^4 [1 - (T_f/T_g)^4]. \qquad (1)$$

which indicates that the effective radiation will be zero for $T_g = T_f$ and negative for $T_f > T_g$. For example, if the fog temperature is $2^{\circ}C$ higher than the ground temperature, the effective radiation will be -0.014 cal/cm^2 min.

The attenuation of the effective radiation by clouds is usually calculated by the equation

$$F_n = F_0(1 - Cn),$$

where n is the amount of low cloud cover and C is the attenuation factor, or (with continuous cloud cover) $F_1 = F_0(1 - C)$, whence the coefficient of relative attenuation of radiation $C = F_0 - F_1/F_0$.

Let us use this equation for fog; after substituting the effective radiation values from table 1, we have C = 0.82, which is in good agreement with the C value for low clouds [1, 8].

Figure 1, plotted from data of individual cases, shows C versus fog thickness. On the other hand, the relative attenuation of radiation can be expressed by the Bouguer-Lambert law

$$\frac{\Delta F}{F_0} = 1 - e^{-km}, \qquad (2)$$

where m = wh.

If we substitute the above value of C (0.82) and the mean values of thickness and liquid-water content of the fog from [4] (220 m and 0.2 g/m^3, respectively) into (2), the attenuation factor for long-wave radiation k will be 450 cm^2/g, which is in satisfactory agreement with the theoretical data [1, 8]. A nomogram (fig. 2) based on the data obtained was plotted to determine the relative attenuation of the effective radiation versus the thickness (h) and liquid-water content (w) of the fog. It is clear from fig. 2 that a fog with w = 0.2 g/m^3 and h = 200 m absorbs practically all long-wave radiation and consequently radiates like an absolutely black body. Observations indicate that even in the case of a thicker fog, the effective radiation of the ground differs from zero. This is explained by the lapse rate within the fog layer.

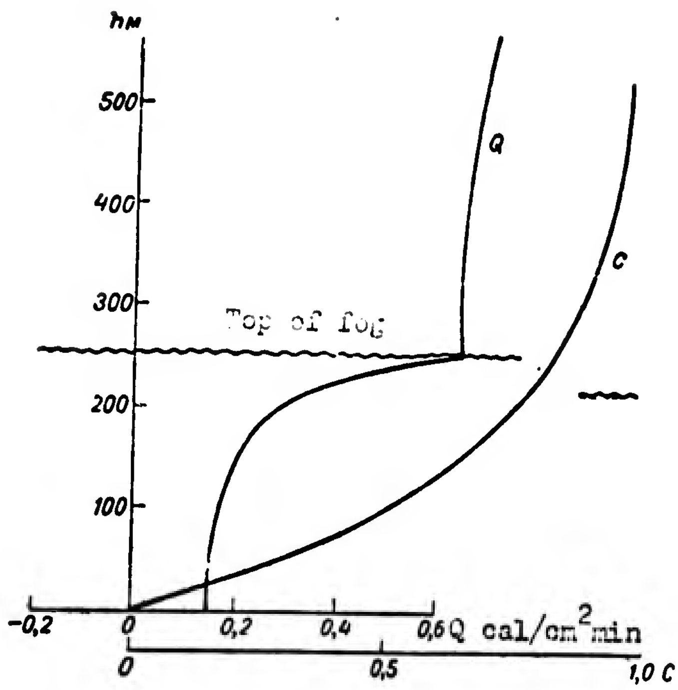

Figure 1. Profile of total solar radiation (Q) and the attenuation factor for long-wave radiation (C) in fog.

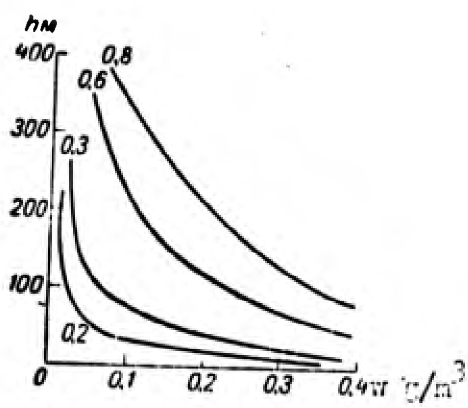

Figure 2. Nomogram for determining the relative attenuation of effective radiation versus liquid-water content and fog thickness.

An approximate formula for the attenuation of the long-wave radiation balance in fog ($\Delta R/R = 0.06$) is given in [8]. If in (2) we expand e^{-km} in a series, the first two terms will be the Shifrin equation. Such an approximation is too rough, however, and is valid only for thin fog layers. In this case, straight lines are obtained on the nomogram (fig. 2). The theory presented in [8] gives a different value for the attenuation factor ($k = 1.2 \times 10^3$ cm^2/g) for fog drops that are commensurate with the wavelength (for waves of approximately 10μ).

In this case, a fog with $w = 0.1\ g/m^3$ and $h = 200$ m radiates practically as an absolutely black body.

In [6], it was found that during the cold part of the year the temperature decrease due to transformation is nearly twice as large for heat transport from the south as it is for heat transport from the west or east. The reason is that when warm air is transported from the south, the temperature decrease due to transformation is caused not only by turbulent heat exchange with the underlying surface, but by the movement of air toward lower radiation balances. This is in agreement with theory.

For example, an approximate formula for the temperature change was obtained in [1]

$$\Delta T = a\Delta R + b\Delta T_0 ,$$

which shows that temperature changes are produced mainly by the horizontal temperature contrast (ΔT_0) along a trajectory and by the difference in the radiation balance (ΔR) at the beginning and end of the trajectory. Here, a and b are coefficients that depend on turbulent exchange, the thermal conductivity of the soil, and other factors. Latitudinally, on the average, $\Delta R = 0$ and the transformational changes are determined by the value of ΔT_0. In the south-north direction, $\Delta R \neq 0$, and the temperature change depends on two terms of the formula. This is valid in a mean diurnal profile. A more complete analysis of the radiation balance, whereby we take the diurnal variation into account, reveals several important details.

Table 3 shows the differences in the radiation balance with latitude and longitude in fogs for five weather stations in the Ukraine. The data indicate that, on the average, the latitudinal difference of the radiation balance is zero, while the longitudinal difference is 0.6 to 1.2 $cal/cm^2\,hr$ for the distances in question. This leads to an individual temperature decrease of 0.5 to 1.0°C/day with south-north movement of air. During the night hours, when the absolute value of the radiation balance is equal to the effective radiation, the indicated difference is opposite in sign and the temperature of a northward moving particle increases.

Table 3

Difference in Radiation Balance Between Stations in Fog (cal/cm^2 hr).

	Observation period (solar time)						Mean diurnal	No. of cases
	0130	0730	1030	1330	1630	1930		
Odessa to Askaniya-Nova	0,0	0,0	0,0	0,0	–0,6	0,0	0,0	156
Kiev to Poltava	–1,2	0,6	0,0	0,0	0,6	–0,6	0,0	105
Askaniya-Nova to Konotop	–0,6	–0,3	3,0	4,8	1,2	–3,0	0,6	167
Askaniya-Nova to Poltava	–0,6	0,0	3,0	4,2	0,6	–0,6	1,2	170

The radiation characteristics at various heights (e.g., at the top of a fog or clouds) are of particular interest. Thus far, however, only a few flights have been made on which radiation characteristics were measured, owing to the great complexity of conducting an experiment on board an aircraft; only a few preliminary conclusions can be drawn from these characteristics.

Figure 1 is the profile of the total solar radiation pressure at a solar elevation of 20 to 25°, in fog and above it. The total solar radiation in the fog at ground level was 0.15 to 0.20 cal/cm^2 sec, while at the top of the fog it was 0.50 to 0.60 cal/cm^2 sec. The albedo was 15 to 20% on the ground and 60 to 80% at the top of the fog. The absorption of solar radiation in a fog layer 250 m thick was 0.03 to 0.04 cal/cm^2 min, causing a temperature rise of 0.2 to 0.3°C/hr. However, inasmuch as the effective radiation in the fog (except for its top) is of the same order of magnitude (see table 1), the fog layer is actually not heated directly by the sun's rays at solar elevations of less than 20 to 25°. At greater elevations, the absorption of solar radiation by the fog proves to be more than the effective radiation, and the fog layer warms up.

If the fog contains a large amount of industrial haze, as at Donetsk, the fog layer is heated by solar energy at much lower solar elevations. This is in good agreement with the results obtained earlier [5], indicating that the fog begins to disperse from below owing to radiational heating of the ground. The total attenuation factor of solar radiation in fog, according to the data in fig. 1, can be determined by the equation

$$I/I_0 = e^{-km} = 0.76,$$

whence

$$k = 0.26/m.$$

The albedo is allowed for in calculating the total value of the solar radiation I at the top of the fog; I_0 is the total solar radiation in the fog at a height of 50 to 60 m or at ground level. In a fog with $w = 0.2\ g/m^3$ and $h = 200$ m, $k = 65\ cm^2/g$, i.e., it is approximately 10 factors less than for long-wave radiation.

The considerable negative radiation balance at the top of a fog or low cloud cover is in good agreement with the large lapse rates in the upper part of the fog. The data of special fog-study flights indicate that at the top of the fog, in 60% of the cases, the lapse rate was greater than the moist-adiabatic gradient (table 4).

Table 4 shows only those cases in which the lapse rate γ was greater than the moist-adiabatic gradient γ_{ma} at the top of the fog. In about 50% of these cases, the true gradient exceeded the moist-adiabatic by $0.5^{\circ}/100$ m or more, i.e., γ was greater than the dry-adiabatic gradient. Despite large values of γ, the cooling was poorly transmitted to the lower layers of fog. In 93% of the cases the thickness of the layer with large gradients was less than 100 m, in 56% of the cases it was less than 50 m. Table 4 shows that the thickness of the layers with the largest γ values was usually less than that of the fog. With large γ values, the fog top assumed the shape of stratocumulus

Table 4

Frequency of Lapse Rates at the Top of Fog, Layer Thicknesses, and Frequency of Fogs of Various Thickness

	Difference $\gamma - \gamma_{ma}$ °/100 m				Layer thickness		
	0,0–0,5	0,51–1,0	1,01–1,50	>1,50	0–50	51–100	>100
Number of cases	36	22	7	5	39	26	5
%	52	31	10	7	56	37	7
	Fog thickness, m						
	00–100	101–200	201–300	301–400	401–500	501–600	>600
Number of cases	6	16	12	14	17	4	2
%	9	26	18	21	25	6	3

clouds. The distribution of fog thicknesses in such cases differs substantially from the distribution when all fogs are taken into account [5]. The first maximum (100-200 m) apparently pertains to radiation fogs, the second frequency maximum to thicknesses of 400 to 500 m, i. e., to fogs of small thickness in general.

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