ATMOSPHERIC INFRARED RADIATION OVER MINNEAPOLIS TO 30 MILLIBARS

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ABSTRACT

This paper presents some of the conclusions from the results of about 300 Black Ball flights in which the total atmospheric infrared radiation is measured in terms of an equivalent radiation temperature. The data presented include typical measurements and a seasonal analysis of the radiation at various pressures. The measurements indicate that the net loss of energy to space by infrared radiation is considerably less than calculations have indicated and cast doubt on some of the assumptions implicit in those calculations.

1. Introduction

The basic theoretical problems connected with the earth's loss of radiant energy to space, due to infrared emission by the surface, by cloud layers, and by the diffuse water vapor, carbon dioxide and ozone, have been adequately treated in literature. Comprehensive treatments of the problem are given, for example, in Elsasser (1942) and Goody and Robinson (1951). As the latter point out, however, there is a paucity of field observations, particularly away from the surface. The author knows of only two reports concerning attempts to measure infrared radiation at higher levels, one, an early measurement from a balloon by von Anders Ångström (1928), and a more recent measurement from a high-altitude aircraft by Houghton and Brewer (1955).

Because of the great variability of such atmospheric parameters as water-vapor density and distribution of clouds, it should be obvious that attempting to predict the general properties of atmospheric radiation from a few observations is much like trying to analyze the general circulation by noting the wind direction and velocity at a few points. In other words, the day-to-day variation in the radiation at some level in the atmosphere, over a particular point, is apt to be just as large as the total variation with season. The measurements reported in this paper show, indeed, that this is the case. Just as with a large sample of wind-velocity measurements, however, a large enough sample of radiation measurements reveals certain long-range trends with season. Probably, with more information, the equivalent sample taken over many degrees of latitude would indicate a consistent variation with latitude as well.

The measurements reported in this paper have all been taken from the vicinity of Minneapolis (45°N). The program initiating the study was begun early in 1953 but did not gain much momentum until the invention of the Black Ball late in 1954. Frequent measurements were taken with the initial model of this instrument, but the quantitative results began accumulating when it was greatly improved by the addition of a convection shield. The Black Ball and its use have been described (Gergen, 1956). A large share of the credit for the invention of this simple instrument, which has allowed these measurements to be obtained, belongs to Drs. Leland Bohl and V. E. Suomi, whose suggestions proved most fruitful.

Essentially, the Black Ball measures a temperature which is proportional to the total (up plus down) incident radiation. Because convection prevents the black absorber from attaining true radiative equilibrium, the observed temperatures must be corrected, the convection (and thermal-time constant) correction serving roughly to double the temperature difference between the air and Black Ball temperatures. The total correction, then, amounts to about five per cent of the absolute value of the equivalent radiation temperature, but about 100 per cent of the temperature difference. It is believed that this correction factor itself is known to within about ten per cent accuracy. Thus, it appears that the measurements lead to an estimate of the equivalent radiation temperature whose absolute value should be accurate to approximately one per cent from the ground to about 50 mb.

Black Ball flights are made at night using an ordinary meteorological radiosonde. The air and Black Ball temperatures are sensed by the same type of thermistor, the white, lead carbonate-coated ML-419/AMT-4.[2] Both thermistors are matched for each flight so as to avoid systematic errors, and in flight, the Black Ball thermistor replaces the humidity element in the radiosonde circuitry. For meteorological pur-

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[2] Friez Instrument Co., Baltimore, Md.

poses, of course, it would be desirable to employ a slightly more elaborate radiosonde pressure-switch which could present information from three or more transducers (air thermistor, Black Ball thermistor, and humidity element), but this was not done in the measurements reported here. It may well be worthwhile to consider making the Black Ball a standard meteorological instrument, however, since as will be shown, the radiative cooling (or warming) of the atmosphere at any point is directly related to the difference between the air and equivalent radiation temperatures.

2. Some mathematical ideas

The general theory of atmospheric radiation has been covered elsewhere, but in order to present the relations governing the results from Black Ball measurements as succinctly as possible, it is necessary to become somewhat rigorous in defining quantities. A fundamental definition is that of the specific intensity. If the amount of energy, dE_ν, in a specified frequency interval $d\nu$, is propagated in the time dt through an area dA into a solid angle $d\omega$, which is inclined at the angle θ to the area dA, then the proportionality function relating that energy to the time and the geometry is the specific intensity, I_ν, at the frequency ν about which the frequency interval $d\nu$ exists:

$$dE_\nu = I_\nu \cos\theta \, dA \, d\omega \, d\nu \, dt. \tag{1}$$

This quantity so defined is *not* the flux passing through dA. For the particular case of a black body, the specific intensity of black radiation is given the special symbol B_ν, and is expressed in terms of fundamental physical constants by means of the well-known Planck formula:

$$B_\nu = (2h\nu^3/c^2)[\exp(h\nu/kT) - 1]^{-1}. \tag{2}$$

This is seen to be independent of the direction angles θ and ϕ, a condition which is not true for a general intensity.

A second definition, that of the specific mass absorption coefficient, κ_ν', concerns itself with the absorption of radiation in a material whose mass density is ρ, upon traversing a path length ds through the material:

$$dI_\nu = -\kappa_\nu' I_\nu \rho \, ds. \tag{3}$$

Various implications of this definition are not always understood. A particularly clear account of the ideas involved is given in Kourganoff (1952).

The fundamental equation which governs the transfer of energy from one part of a system to another is given by

$$\frac{dI_\nu}{\rho ds} = -\kappa_\nu(I_\nu - B_\nu), \tag{4}$$

where the new coefficient, κ_ν, appearing in this equation, is related to that in (3) by

$$\kappa_\nu = \kappa_\nu'[1 - \exp(-h\nu/kT)]. \tag{5}$$

Although the distinction here is not great except at long wave-lengths, it is frequently ignored altogether. A detailed analysis of the derivation of (4) is given in Chandressekhar (1939), pp. 183 ff.

For the atmosphere, ρ and κ_ν are determined by the nature and concentration of those constituents which absorb in the infrared. For atmospheric work, it is convenient to define a path length $du = \rho dz$ (gm/cm²), where z is the vertical height directed upward. Then, if the angle θ is taken to be the angle between the *positive* directions of u and I_ν, it is also convenient to regard two specific intensities, one which propagates energy only upward through a plane, $I_\nu\uparrow$, and another which propagates energy only downward through a plane, $I_\nu\downarrow$. With these conventions, one form for the two intensities at a height u (gm/cm²) is,

$$I_\nu\uparrow(u) = B_\nu(0)\exp\left(-\sec\theta\int_0^u \kappa_\nu(x)dx\right) + \int_0^u \kappa_\nu(w)\sec\theta B_\nu(w) \times \exp\left(-\sec\theta\int_w^u \kappa_\nu(x)dx\right)dw \tag{6}$$

$$I_\nu\downarrow(u) = I_\nu\downarrow(u_m)\exp\left(-\sec\theta\int_u^{u_m}\kappa_\nu(x)dx\right) + \int_u^{u_m}\kappa_\nu(w)\sec\theta B_\nu(w) \times \exp\left(-\sec\theta\int_u^w \kappa_\nu(x)dx\right)dw. \tag{7}$$

Here, $B_\nu(0)$ is the upward specific intensity at the surface ($u = 0$), where the surface is assumed to be black, $I_\nu\downarrow(u_m)$ is the downward specific intensity at the height u_m (often conveniently taken as infinity, making $I_\nu\downarrow(u_m)$ identically zero), and where x and w are dummy variables of integration replacing u. This solution is rigorously true, assuming only local thermodynamic equilibrium (*cf.* Kourganoff, 1952) and plane stratification of the atmosphere.

In practical work, it is frequently convenient to define an *equivalent radiation temperature*, T_r, which is the temperature assumed by a perfectly black body of specified shape when a known specific intensity is incident on the body, convection and conduction being assumed negligible. For the case of a *spherical* black absorber at the level u in the atmosphere,

$$\sigma T_r^4(u) = \frac{\pi}{2}\int_0^\infty d\nu\int_0^{\pi/2}[I_\nu\uparrow(u) + I_\nu\downarrow(u)]\sin\theta\, d\theta. \tag{8}$$

which leads, on using (6) and (7), to

$$\sigma T_r^4(u) = \frac{\pi}{2}\int_0^\infty B_\nu(0)E_2\left(\int_0^u \kappa_\nu(x)dx\right)d\nu$$
$$+\frac{\pi}{2}\int_0^\infty d\nu\int_0^u \kappa_\nu(w)B_\nu(w)E_1\left(\int_w^u \kappa_\nu(x)dx\right)dw$$
$$+\frac{\pi}{2}\int_0^\infty I_\nu\downarrow(u_m)E_2\left(\int_u^{u_m}\kappa_\nu(x)dx\right)d\nu$$
$$+\frac{\pi}{2}\int_0^\infty d\nu\int_u^{u_m}\kappa_\nu(w)B_\nu(w)E_1\left(\int_u^w \kappa_\nu(x)dx\right)dw. \quad (9)$$

This may be transformed by means of an integration by parts to

$$\sigma T_r^4(u) = \pi\int_0^\infty B_\nu(u)d\nu$$
$$-\frac{\pi}{2}\int_0^\infty d\nu\int_0^u \frac{\partial B_\nu(w)}{\partial w}E_2\left(\int_w^u \kappa_\nu(x)dx\right)dw$$
$$+\frac{\pi}{2}\int_0^\infty d\nu\int_u^{u_m}\frac{\partial B_\nu(w)}{\partial w}E_2\left(\int_u^w \kappa_\nu(x)dx\right)dw. \quad (10)$$

In equations (9) and (10), $E_1(z)$ and $E_2(z)$ are the exponential integrals of the argument z, defined as $E_n(z) = \int_1^\infty \xi^{-n}\epsilon^{-\xi z}d\xi$. Expression (10) is the starting point for any numerical analysis of atmospheric radiation. Again, no further approximations have been made in obtaining these relations.

The physical interpretations of (6) and (7) are quite straightforward. Equation (6) simply asserts that the specific intensity reaching the level u in the atmosphere consists of two parts: the first, that which originates at the (black) surface of the earth, $B_\nu(0)$, attenuated by an exponential function in passing through the atmosphere from the surface to the level u, and the second, that which originates within each layer, dw, of atmosphere between the surface and the level u, $\kappa_\nu(w)\sec\theta B_\nu(w)$, attenuated in passing through the levels between that level w and the level u. Equation (7) has a similar interpretation. The temperature expressions (9) and (10) are somewhat more complicated since an integration over the direction angles is included in the expressions. The first term in the latter, however, immediately reduces to $\sigma T_a^4(u)$, where $T_a(u)$ is the air temperature at the level u, the remaining two terms accounting for the net excess or lack of radiation at u needed to produce radiative equilibrium.

The above expressions are applicable to an atmosphere containing an arbitrary number of absorbers, by defining the ρ and κ_ν as the sum of ρ and κ_ν for each absorber: $p\kappa_\nu = \rho\kappa\nu_1 + \rho\kappa\nu_2 + \cdots$. The numerical solutions to these equations, however, are most formidable. A method employing graphical integration was outlined by Mugge and Möller (1932) and utilized by Elsasser (1942), but the radiation chart, on which the integration is performed, is strictly limited to a *single* absorber unless the concentration ratios of the two or more absorbers remain constant.

Another quantity of particular interest to the meteorologist is the radiative cooling or warming of a layer of atmosphere. The expression (for an infinitely thin layer) most frequently seen is

$$c_p\frac{\partial T_a(u)}{\partial t}\times\rho_a/4\rho = -\frac{\pi}{2}\int_0^\infty d\nu\int_0^{\pi/2}\left[\frac{\partial I_\nu\uparrow(u)}{\partial u}-\frac{\partial I_\nu\downarrow(u)}{\partial u}\right]\times\cos\theta\sin\theta\, d\theta. \quad (11)$$

If one uses the transfer equation, (4), to substitute for the derivatives, it is easy to transform (11) to

$$c_p\frac{\partial T_a(u)}{\partial t}\times\rho_a/4\rho = \frac{\pi}{2}\int_0^\infty d\nu\int_0^{\pi/2}\kappa_\nu(u)[I_\nu\uparrow(u)+I_\nu\downarrow(u)]\times\sin\theta\, d\theta - \pi\int_0^\infty \kappa_\nu(u)B_\nu(u)d\nu. \quad (12)$$

If one now defines a mean absorptivity (independent of frequency), $\bar\kappa(u)$, at the level u, by means of the relation,

$$\bar\kappa(u)\int_0^\infty B_\nu(u)d\nu = \int_0^\infty \kappa_\nu(u)B_\nu(u)d\nu, \quad (13)$$

then it may well be possible to use this *same* mean absorptivity for the first term of (12). Under this assumption, a comparison of (13) with (8) serves to show that the equivalent radiation temperature difference for a spherical absorber, such as the Black Ball, is related to the radiative cooling by the expression,

$$c_p\frac{\partial T_a(u)}{\partial t}\times\rho_a/4\rho = \bar\kappa(u)4\sigma T_a^3(u)\theta_r(u), \quad (14)$$

where θ_r is defined as $\theta_r(u) = T_r(u) - T_a(u)$.

It is not at all obvious that the two mean absorptivity coefficients, one from the first term on the right in (12) and one from the second term, as in (13), are really the same. But there is good reason to believe that they are not greatly different, since experiment indicates that, although the atmosphere is most certainly *not* in radiative equilibrium, neither is it very far removed from it. Definite confirmation of the assumption will appear after completion of an analysis using the newer absorption data (Howard, Burch, and Williams, 1955; Plass, 1956a, 1956b).

To complete this section, one further result from the above expressions should be noted. If one inquires into the sensitivity of an expression like (9) on the accuracy of the absorption coefficient, it appears that the radiation temperature is very insensitive to the value of κ_ν itself. Assume a fixed-surface temperature of, say, 280C, and a standard atmosphere, and then allow κ_ν to vary from zero to infinity. A plot of the variation in $T_r(u)$ with this variation in κ_ν is very instructive.

The same insensitivity is not present, however, when one considers the variation of κ_ν with u (pressure, for example). As Strong and Plass (1950) rightly point out, the pressure-broadening of spectral lines is the primary controlling factor in a radiative heat-transfer calculation.

3. Experimental results

The corrected Black Ball results lead to a value for the equivalent radiation temperature, and are thus connected with the properties of atmospheric radiation through (10). Soundings are taken at night, usually within a few hours of sunset, depending on the season, and for each flight, the air and Black Ball temperatures are read out at each radiosonde pressure-switch contact. After applying the correction at each pressure-point, the air and equivalent radiation temperatures are plotted out for each of these points. This was done in this work in order to have as convincing an argument as possible that the corrected Black Ball temperatures represent as closely as possible a radiation temperature in accord with the definition. Since the corrected radiation temperature is about once again as far from air temperature as the observed Black Ball temperatures, an indication of the validity of the correction expressions is found in the regularity of the curve which results from correcting the temperatures at each individual pressure-point. The fact that the plotted points show a reasonably smooth variation with pressure, especially through the crossover points, is a suggestive indication that the results satisfy this criterion. It must be emphasized that these plotted points for individual flights are not smoothed except insofar as the velocity and lapse rates which enter into the correction function are obtained for a particular pressure-point by taking the average of those quantities for the two adjacent pressure-intervals (Gergen, 1956).

Although it is manifestly impossible to present all of the collected data, there is a number of typical cases which warrant special attention. One such case is that of the radiation temperature on a clear summer night. Fig. 1 is a plot of the air and equivalent radiation temperatures for RA-135 on the night of 18 August 1955. In addition to the observed radiation temperature, those for the levels 700, 500, 300, and 150 mb, calculated by using the Elsasser chart with the square root (crossed circles) and linear (dotted circles) pressure correction (Kaplan, 1952a), are also shown for comparison.

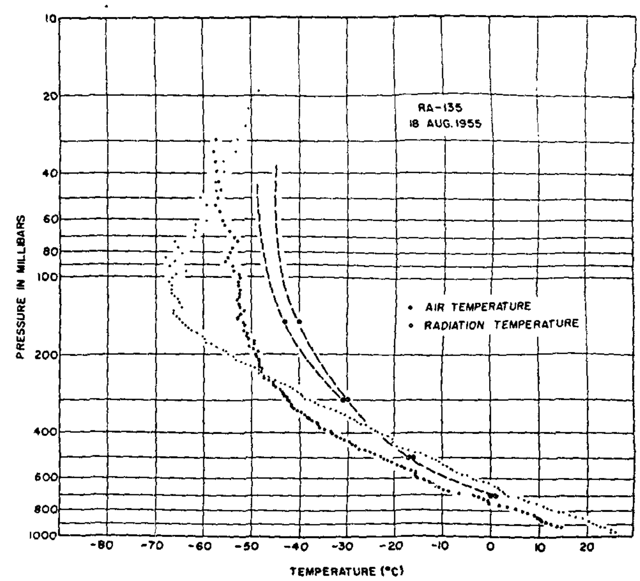

FIG. 1. Air and radiation temperatures over Minneapolis for 18 August 1955.

It is apparent immediately, that qualitatively, all three radiation temperatures behave in much the same way. However, there are significant points of difference. The observed radiation temperature crosses the air temperature at about 240 mb, while the calculated temperatures cross at about 380 mb. This point is considered to be particularly significant, since the Black Ball is not subject to convection at the point where the temperature difference vanishes. Further inspection of the plot reveals the interesting observation that, while the *values* for the square-root pressure correction-curve are nearest those observed, the *shape* of the linear-pressure correction-curve is more nearly in agreement with the observed shape. It must be emphasized again that the Elsasser radiation chart applies to a horizontal disk, whereas the Black Ball is spherical, so a small difference is to be expected. This expected difference, however, is much less than the difference indicated in fig. 1.

In agreement with qualitative ideas, the radiation temperature at great heights approaches a constant. This is, of course, merely a reflection of the fact that at sufficient altitudes, there is simply not much material left to absorb or radiate. The value of this temperature is considerably lower than that predicted by calculation, a fact which implies the loss of much less energy to space than has been supposed. For this flight, for example, the observed radiation temperature at 50 mb is -57C, while those calculated for the linear and square-root pressure-correction, respectively, are -45C and -49C. These three temperatures correspond to radiated powers of 12.4, 15.3, and 14.3 mw/cm^2, respectively. The calculated values are thus too high by about 20 per cent.

A second typical case is that for a clear winter night.

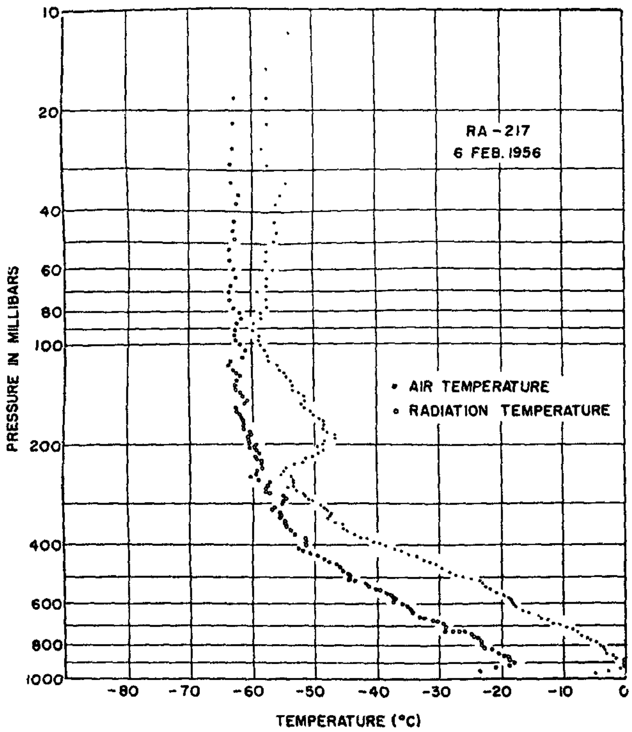

FIG. 2. Air and radiation temperatures over Minneapolis for 6 February 1956.

This is illustrated in fig. 2, which shows the results from RA-217, flown over Minneapolis on the night of 6 February 1956. Here, the shape of the radiation temperature-curve with altitude remains much the same as for summer, except that it has been bodily displaced to the cold, while the curve of air temperature is qualitatively and quantitatively different. The net result, very important from a meteorological standpoint, is that in the winter (on clear nights), the atmosphere everywhere is being *cooled* by radiation, in contrast to the case for summer, where a large region of the atmosphere near the tropopause is being *warmed*.

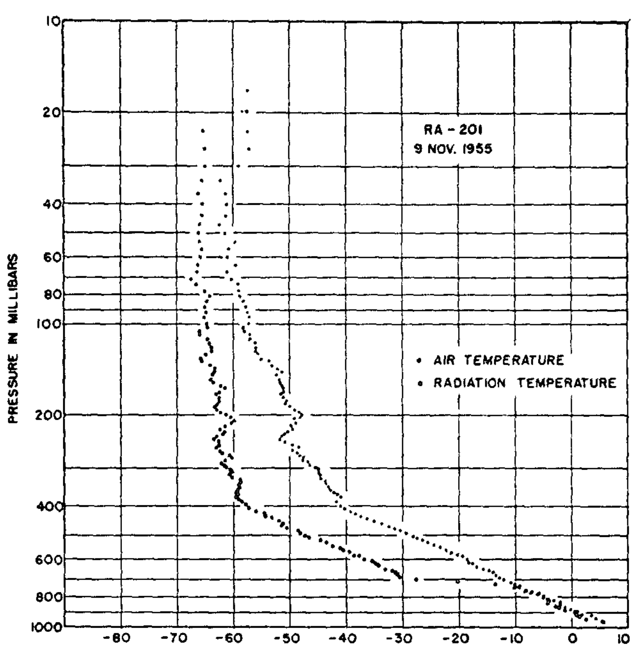

FIG. 3. Air and radiation temperatures over Minneapolis for 9 November 1955.

A third case of special interest shows the effect of a very thick, low-lying cloud layer. Fig. 3 shows results from RA-201, flown over Minneapolis on the night of 9 November 1955. Weather Bureau reports for the area during the period of the flight show a complete overcast, measured at between 2700 and 3000 feet. The effect of the cloud is clearly evident in the plot. Since the cloud is at air temperature and very dense, the radiation temperature everywhere within the cloud must be just the air temperature. Immediately above the cloud, the radiation quickly assumes a very much colder value, a result which is easily interpreted in terms of the temperature of the cloud *top*, which is seen to be about −10C. For all regions above the cloud, the radiation behaves much as though the earth's surface were replaced by a perfectly black surface at −10C, and the upward radiation is, accordingly, much less than it would be on a clear night.

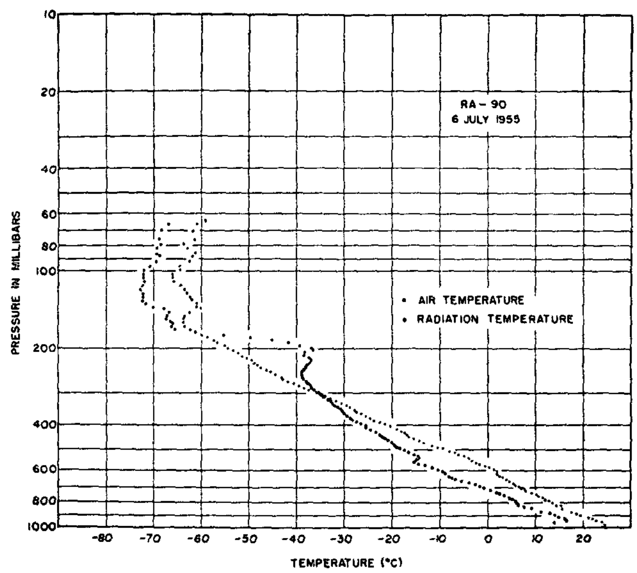

FIG. 4. Air and radiation temperatures over Minneapolis for 6 July 1955.

The situation for high clouds is somewhat similar, though one would not expect to find such clouds acting as black as those at lower levels, due to the inability of the atmosphere to contain as much moisture at the colder temperatures. Multiple cloud layers produce behavior which can be imagined as a superposition of effects.

The last special case of particular interest is that for the anomalous high clouds, illustrated in fig. 4, for RA-90, 6 July 1955. During the flight, the Weather

Bureau reported only 0.4 coverage for a short time at 3500 feet, and no high clouds at all. Nevertheless, as can be seen from the sounding, there was evidently a very dense absorber at about 40,000 feet. The great decrease in the radiation temperature immediately above 200 mb suggests that the attenuation of the upward radiation is nearly complete, and yet from the behavior of that temperature at lower levels, the cloud layer does not appear to be very thick. Furthermore, the presence of sufficient water vapor at that level, needed to produce such attenuation, seems to be very questionable. The radical behavior shown in this flight is by no means unique. Numerous flights have shown correspondingly large (and larger) attenuations existing at these levels.

This particular flight, however, is a very clear-cut example in that no high clouds were apparently visible at all,[3] and certainly could not have been detected with a humidity element which does not respond below −40C. It might be suggested that the absorber is not water vapor at all. For example, V. E. Suomi[4] has suggested that particulate matter at or near the tropopause may exert a considerable influence on radiative behavior, or again, one may choose to assign to ozone a prominent role. Whatever the reason for the anomalously large absorption shown here, there appears to be no question that it has existed on many occasions and is very difficult to explain in terms of water vapor absorption.

4. Seasonal averages

In order to present the collected data in as explicit a form as possible, monthly averages of the data were prepared, independent of the cloudiness, altitude attained, etc. The averages were obtained by forming a simple average of all air temperatures or radiation temperatures which fell into a two-per cent pressure interval. Because of the nonlinearity of the radiosonde pressure-switch and also because of the variability in maximum altitude attained, there are more points in each pressure interval near the surface than there are at higher altitudes. This in part accounts for the larger error bars drawn at high altitudes in the figures. The points plotted are for convenient pressures, the values of the temperatures at those points being read off from the plot of the averages. The error bars represent roughly the estimated error due to statistical scatter and probable error in the measured temperature.

Monthly average data is presented in figs. 5–13 for the months of February through October, inclusive. Because of unavailability of radiosonde equipment for a time, the number of soundings taken during the months of November, December, and January are too few to justify averaging, and accordingly, no averages are presented for these months.

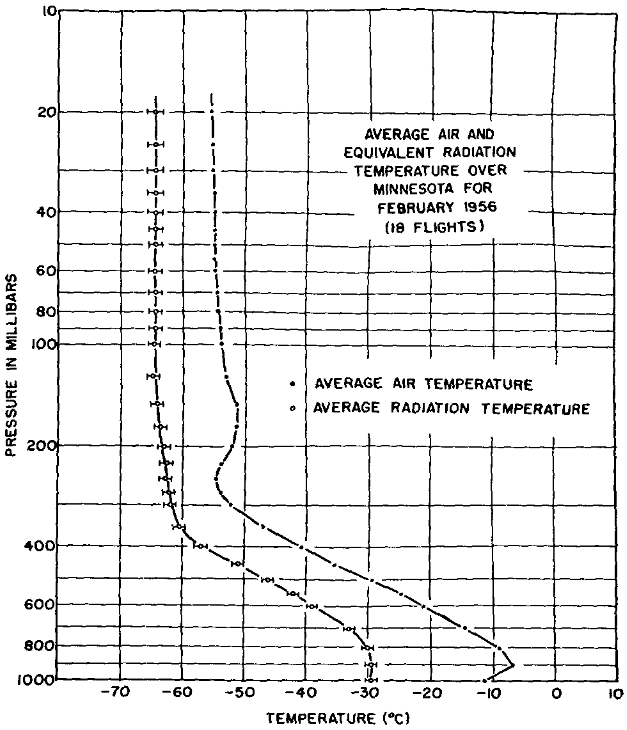

Fig. 5. Average air and equivalent radiation temperature over Minnesota for February 1956.

5. Discussion of results

As pointed out in section 2, there is little possibility of making a serious error (for example, 50 per cent) in a calculation of the equivalent radiation temperature,

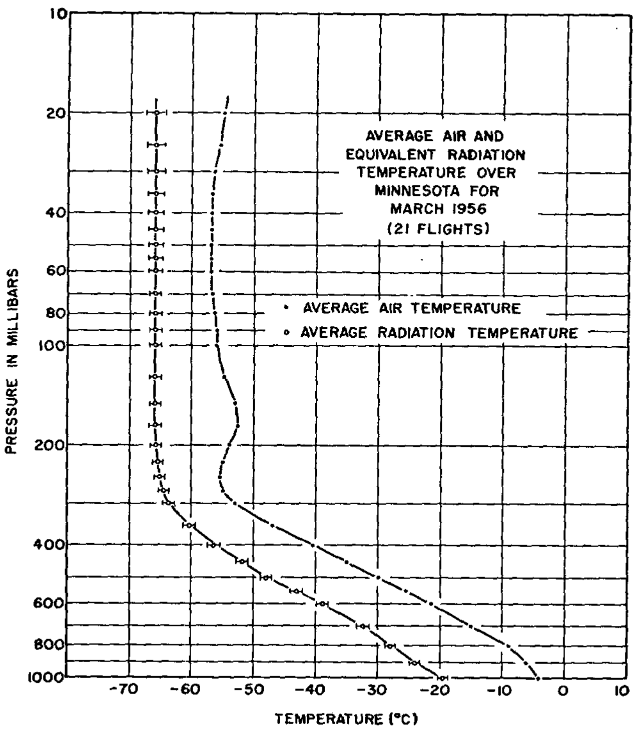

Fig. 6. Average air and equivalent radiation temperature over Minnesota for March 1956.

[3] Further investigation of the meteorological conditions during this flight by Dr. H. T. Mantis allows the possibility of the balloon having moved into a region of cirrus clouds. These flights showing anomalously high absorptions will be treated in greater detail later.

[4] Personal communication.

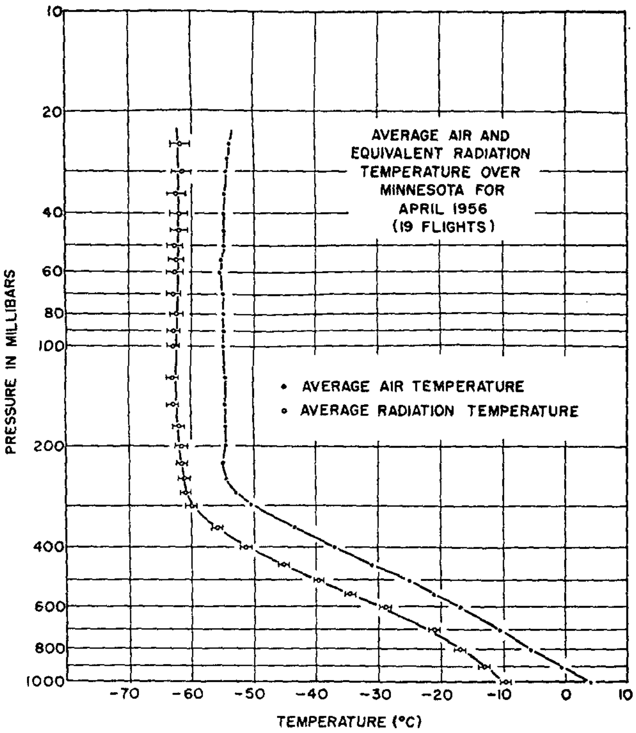

FIG. 7. Average air and equivalent radiation temperature over Minnesota for April 1956.

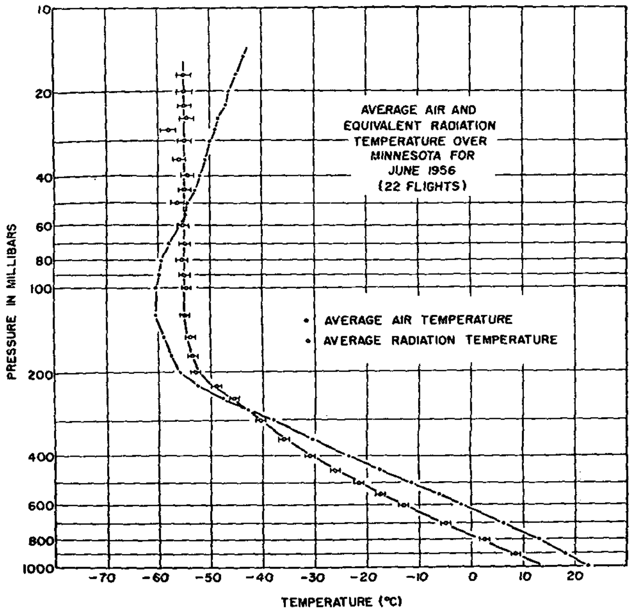

FIG. 9. Average air and equivalent radiation temperature over Minnesota for June 1956.

by using either the Elsasser chart or a numerical method for evaluating (10). The detailed analysis of atmospheric absorption which is required to produce accurate values of the radiation with altitude is so complicated, however, that existing methods of analysis seem incapable of attaining greater than first approximation accuracy. A more complete discussion of the measured values of the radiation temperature in relation to the calculated values will be given at a later time, but a few remarks will point out the trend of this relation.

Fig. 1 illustrates the comparison between the observed and calculated radiation temperatures using both pressure corrections to the Elsasser chart. The fact that the actual loss of energy to space is less than that calculated means that estimates of the average albedo of the earth's surface and of clouds must be re-examined. Moreover, proposed mechanisms for the attenuation of infrared radiation in a system like the atmosphere can be checked by comparison of predicted results with observed results. The approximations by means of which exponential integrals of integrated absorptions (cf. [10]) are reduced to ex-

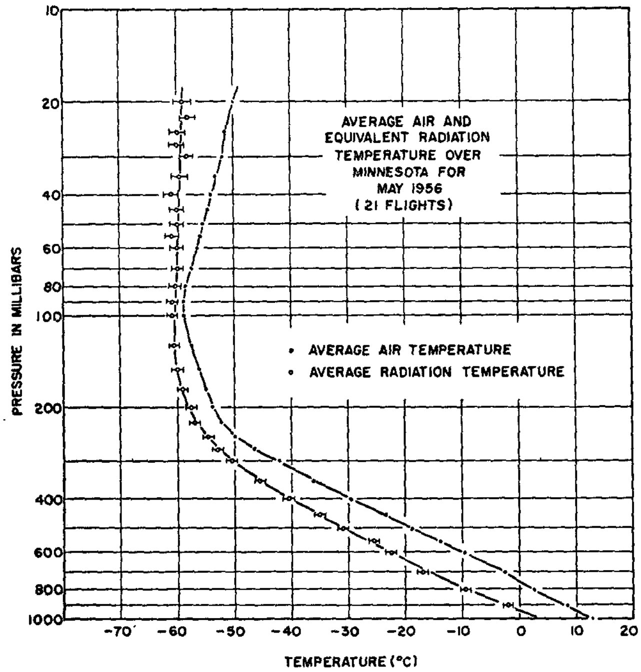

FIG. 8. Average air and equivalent radiation temperature over Minnesota for May 1956.

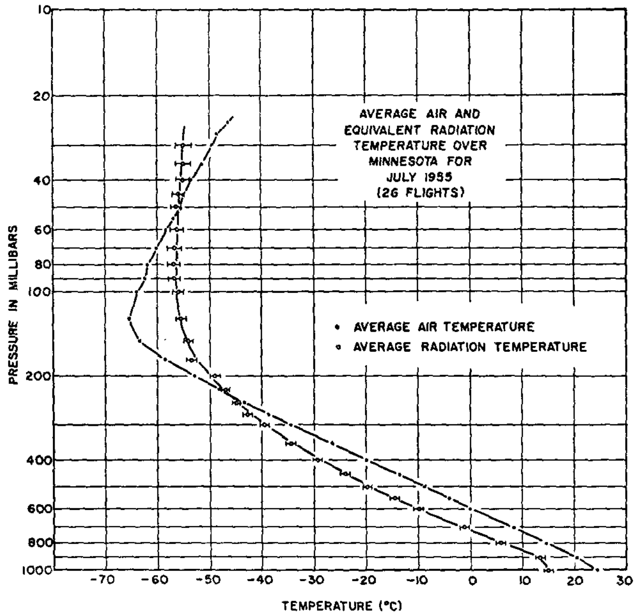

FIG. 10. Average air and equivalent radiation temperature over Minnesota for July 1955.

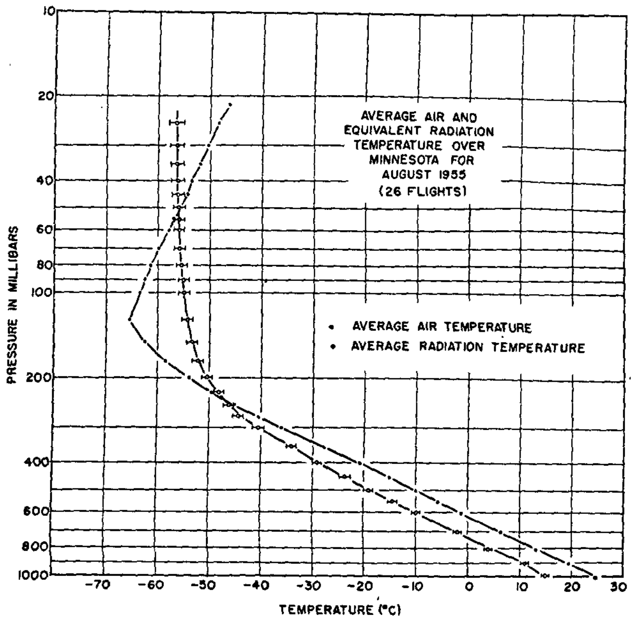

FIG. 11. Average air and equivalent radiation temperature over Minnesota for August 1955.

ponentials of absorption over a fixed path must be more carefully examined, and the newer absorption data such as that of Howard, Burch, and Williams (1955) and Plass (1956a, 1956b) will allow more reasonable approximations to be made. Various discussions of this problem have appeared, for example, Kaplan (1952b), Plass and Warner (1952), Plass (1952), and Godson (1955a, 1955b).

Calculations with the Elsasser chart make use of the supposition that thick clouds behave essentially like perfect absorbers, and can thus be replaced in the calculations by a black surface at the temperature T.

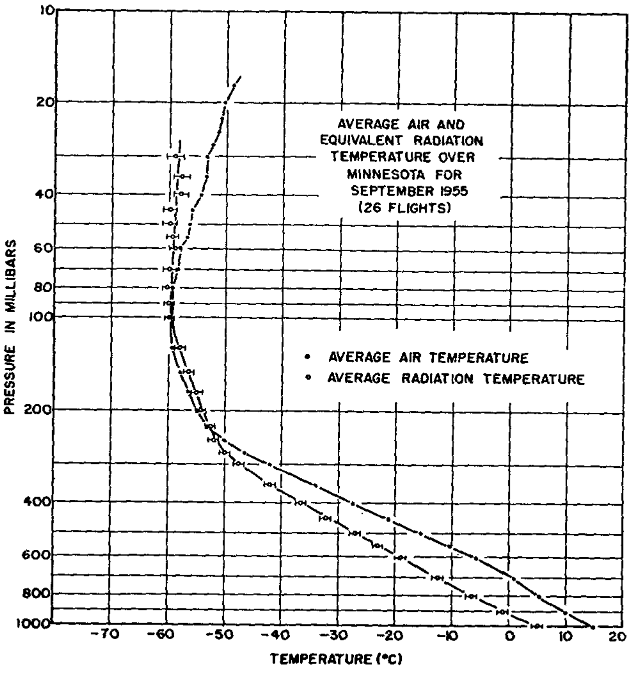

FIG. 12. Average air and equivalent radiation temperature over Minnesota for September 1955.

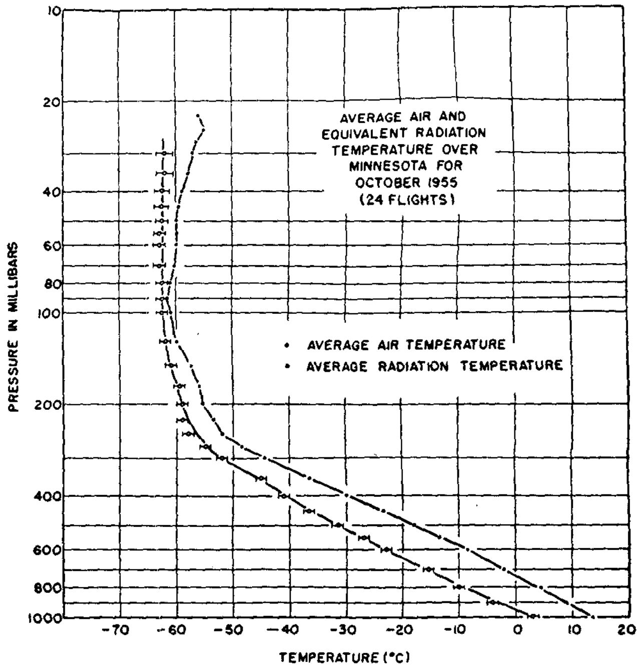

FIG. 13. Average air and equivalent radiation temperature over Minnesota for October 1955.

The question remains, what is the temperature T? The supposition itself is borne out in the Black Ball measurements, as can be seen from an inspection of figs. 3 and 4. However, in these results, it is a simple matter to locate the top of the cloud (or what is more important, the effective *radiating* top of the cloud) and thus to determine the effective temperature of the cloud top. This is not, in general, possible by observing a standard meteorological sounding carrying a humidity element, because of the time lag in that element. For thick clouds, especially at high altitudes, the assumption of an incorrect temperature for the cloud top leads to disastrous results for radiation temperatures above that point.

Another moot point arises when one asks just how thick a cloud must be to be considered perfectly black. As fig. 4 well indicates, the optical determination of blackness is not necessarily correlated with infrared absorption. For this flight, it appears necessary to assume a fairly thin, but intensely black layer of absorber somewhere near 200 mb, although visual observation revealed no trace of clouds in the sky at or near that level.[5] Black Ball measurements, then, bear out the assumption that thick clouds can be considered as black radiators, but cast serious doubt on the applicability of the assumption.

The behavior of the radiation temperature with respect to that of the air temperature in the vicinity of the tropopause is worthy of considerable study. It is apparent from the curves of seasonal variation, figs. 5 through 13, that a considerable portion of the atmosphere near the tropopause is being warmed during the summer at Minneapolis latitudes (45°N). It appears,

[5] See previous comment in footnote 3.

also, that during these months, the stratosphere as such does not exist, the air temperature assuming an increase with height immediately above the tropopause. Although the present set of measurements does not extend to sufficient heights to be able to say that this increase continues at greater altitudes, support is lent to this view by measurements of various kinds (Best, Havens, and LaGow, 1947; Benesch, 1949; Havens, Koll and LaGow, 1952). This temperature structure at high altitudes is important, since there is abundant evidence available indicating that absorption in this region is not negligible.

In the winter, the average values of the radiation and air temperatures are such that at no place in the atmosphere is the radiation temperature warmer than the air temperature. At the same time, it appears that a well-developed stratosphere does exist, apparently to about 20 mb in February. Whether these two observations bear a causal relationship to one another (at least in part) or whether both result independently from other considerations is a matter for future analysis. In any case, the greatly different aspect of the soundings in summer and winter certainly bears on the problem of the atmospheric circulation.

Inspection of the monthly averages reveals the interesting observation that while both the air and radiation temperatures vary greatly with season at high levels (say 100 mb), the variation is in the opposite sense. The property of the colder air temperatures in summer than in winter has received previous comment, but the fact that the radiation temperature at great levels varies directly with the ground temperature seems to have been ignored. At 100 mb, the air temperature for monthly averages during 1955–56 varied between −55C in February to −64C in July, while the variation in the average of the radiation temperature at this altitude for the same period was from −55C in July to −67C in March.

From this, one might be tempted to predict that as far as radiation effects are concerned, a lower latitude in winter might behave much as does a higher latitude in summer. Such a prediction does not appear to be supported by the small amount of data so far collected on latitude effects, but the amount of definite evidence is as yet so meager that the idea is not completely discredited. It is known that the water vapor content of the atmosphere exercises a considerable effect on the radiation temperatures, and there is no intrinsic reason why the humidity variation with latitude at one season should be the same as the temperature variation with season at one latitude. Further observations at various latitudes are needed.

Despite the small size of the sample averaged, it appears that both air and radiation temperatures show a consistent variation with season. Table 1 presents the averaged data for February through October at the following pressure levels: 1000, 700, 500, 300, 200, and 100 mb. In each month, the radiation temperature at 100 mb is essentially that measured at still higher levels.

The data from table 1, plotted against a time scale on which the unit of time is one month, shows a variation which is remarkably well-fitted by a simple sine curve. A Fourier analysis of these data, using only terms of fundamental frequency, is shown in figs. 14 and 15. Even though the sample is small, it can be seen that the best fit to the data shows a constancy of phase angle with altitude, except for the air temperature data at 700 mb. In other words, the best fit maxima are separated from one another by less than half a month. The Fourier amplitudes and phase angles for the two temperatures are given in table 2. Note that the air temperature at 100 mb shows the familiar 180-degree phase shift.

A plot of the amplitudes of the radiation temperature against pressure indicates that the amplitude decreases exponentially with altitude. This is approximately what one would expect, assuming that the direct ground radiation term in (9) (the $B_\nu(0)$ term) contributes a large share of the energy reaching higher levels. The amplitude exponential decrease with altitude is expressible as

$$A = 22.5\ (p/1000)^{0.58}, \tag{15}$$

where p is in mb. This formula is purely empirical, of course, and has no theoretical justification apart from the sketchy argument above.

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TABLE 1. Average values of air and radiation temperatures at various pressures, February through October.

	1000 mb		700 mb		500 mb		300 mb		200 mb		100 mb	
	T_a	T_r	T_a	T_r	T_a	T_r	T_a	T_r	T_a	T_r	T_a	T_r
Feb	−11.5	−29.0	−15.0	−32.0	−29.5	−46.0	−53.0	−62.0	−52.0	−63.5	−54.5	−65.0
Mar	− 9.0	−20.0	−15.0	−32.0	−30.0	−48.0	−53.0	−63.5	−54.0	−65.0	−56.0	−67.0
Apr	3.0	− 9.5	−11.0	−22.0	−25.0	−39.5	−50.5	−60.0	−54.5	−62.0	−55.0	−64.0
May	13.0	4.0	− 3.0	−17.0	−19.0	−31.0	−43.0	−51.0	−54.0	−58.0	−59.0	−62.0
Jun	23.5	13.5	6.0	− 5.5	−11.5	−22.0	−38.5	−41.0	−56.5	−53.5	−60.0	−55.0
Jul	26.0	20.0	8.0	− 0.5	− 9.0	−20.0	−35.0	−40.0	−53.0	−50.0	−64.0	−55.5
Aug	25.0	16.0	6.0	− 2.0	−10.0	−19.0	−36.5	−40.5	−54.0	−51.0	−63.5	−55.0
Sep	15.0	4.5	0.5	−13.5	−16.0	−28.5	−43.0	−49.0	−55.0	−55.0	−60.0	−59.5
Oct	14.0	2.0	− 2.0	−15.5	−18.0	−33.5	−44.5	−53.0	−55.5	−59.0	−61.0	−63.0

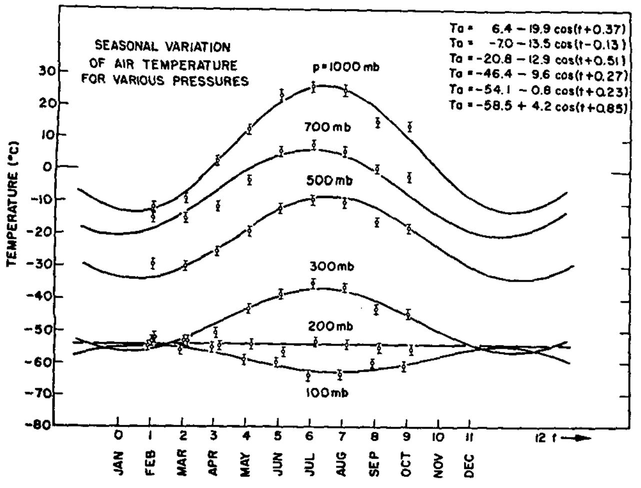

FIG. 14. Seasonal variation of air temperature for various pressures.

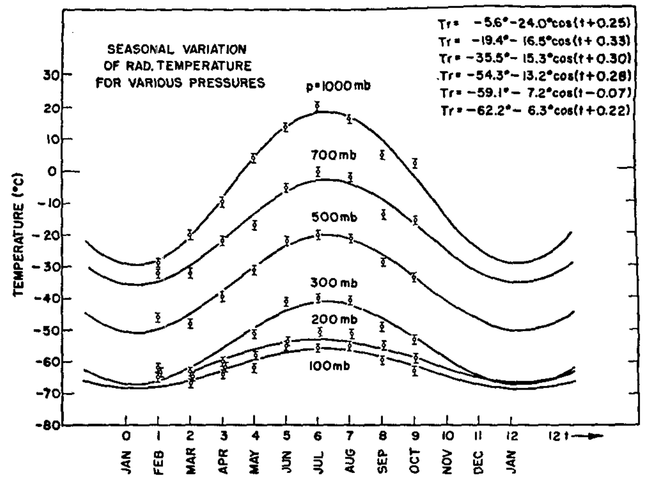

FIG. 15. Seasonal variation of radiation temperatures for various pressures.

TABLE 2. Fourier analysis of the seasonal variation in air and radiation temperatures.

1000 mb	T_a =	$6.4° - 19.9° \cos (t + 0.37)$
	T_r =	$-5.6° - 24.0° \cos (t + 0.25)$
700 mb	T_a =	$-7.0° - 13.5° \cos (t - 0.13)$
	T_r =	$-19.4° - 16.5° \cos (t + 0.33)$
500 mb	T_a =	$-20.8° - 12.9° \cos (t + 0.51)$
	T_r =	$-35.5° - 15.3° \cos (t + 0.30)$
300 mb	T_a =	$-46.4° - 9.6° \cos (t + 0.27)$
	T_r =	$-54.3° - 13.2° \cos (t + 0.28)$
200 mb	T_a =	$-54.1° - 0.8° \cos (t + 0.23)$
	T_r =	$-59.1° - 7.2° \cos (t + 0.07)$
100 mb	T_a =	$-58.5° + 4.2° \cos (t + 0.85)$
	T_r =	$-62.2° - 6.3° \cos (t + 0.22)$

as those who have spent a large amount of time reducing the data to their final form. Messrs. Howard, Maas, Hanson, Anderson, and Stoddart have done much of the actual flight work and by means of their technical proficiency have kept the problems of telemetering to a minimum. Dick Atneoson, Bob Tennison, John Kroening and Henry Byerly have done the careful work of computing the radiation temperatures from the raw data on the University of Minnesota's IBM computer, and the construction of the Black Balls has been well performed by Don Hanson and Ed Beckman.

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