MEASUREMENTS OF INFRARED RADIATION DIVERGENCE IN THE ATMOSPHERE WITH THE DOUBLE-RADIOMETER AND THE BLACK BALL

Roger L. Aagard
University of Minnesota
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ABSTRACT

A double-radiometer for measuring infrared radiation divergence in the atmosphere is described. Three soundings with this instrument and the black ball are compared. General agreement exists between the radiometer divergence measurements and the divergence computed from the black-ball data. One sounding indicates that the atmosphere can be warmed by infrared radiation where the black ball is warmed above air temperature. An atmospheric emissivity has been computed from the radiometer data and compared with the relative humidity.

1. Introduction

The infrared radiation-divergence in the atmosphere may be expressed as

\[ C_p \rho \frac{\partial T_a}{\partial t} = - \sigma \frac{\partial}{\partial Z} (T_1^{4} - T_4^{4}) \]  \hfill (1)

where \( C_p \) is the specific heat of air, \( \rho \) is the density of air, \( T_a \) is the air temperature, \( Z \) is the height taken positive upward, and \( T_1 \) and \( T_4 \) are the temperatures of imaginary infinite planes, just above and just below the level \( Z \), which would produce the same radiation flux per horizontal square centimeter as the atmosphere does.

Usually in practical work the divergence is obtained from a measurement of the upward and downward temperatures at various levels in the atmosphere. This is illustrated in fig. 1.

Gergen [1], however, has suggested that the divergence may be related to the sum of the upward and downward radiation that he has measured with the black ball [2]. Brewer and Houghton [3], among others, do not accept this approach. They point out that the black-ball technique indicates the places in the atmosphere where a black body would be warmed or cooled, and, since the atmosphere is far from a black body, they contend that it is impossible to obtain information about the divergence from the black-ball data. Suomi et al [4] have undertaken to show, on the basis of a sounding with their Economical Net Radiometer [5], that the atmosphere is actually being cooled where the black ball shows warming. Plass [6] has indicated disagreement with Gergen's method by doing an experimental calculation. Möller [7] also raises basically the same objection as the others. He goes directly to the point where Gergen has called the absorption and emission coefficients equal and thus was able to factor them from his equation. Möller has calculated average coefficients for black-body radiation and for atmospheric radiation. These coefficients are not equal. He concludes, therefore, that it is impossible to perform the factorization in the manner proposed by Gergen.

Gergen [8], in a reply to Suomi et al, has given a clear discussion of the problems involved in obtaining reliable divergence data. The major difficulty occurs in taking the difference of a difference as in the equation accompanying fig. 1. The double difference leads to extremely large errors as the magnitude of the divergence becomes small.

There are at least two ways in which the accuracy of divergence measurements can be improved. First, measurements can be made at several constant altitudes instead of allowing the measuring instrument to rise continuously through the atmosphere. Thus, lapse-rate effects are eliminated. Second, radiated power can be measured instead of the temperature of a surface. This immediately gives better accuracy by a factor of four, and, at the same time, convection is eliminated. These two factors provide the basis upon which the double-radiometer experiment was designed.

\[ \sigma \frac{\partial T_1^{4}}{\partial t} \left( \frac{Z}{Z+\Delta Z} \right) = \sigma \frac{\partial T_4^{4}}{\partial t} \left( \frac{Z}{Z+\Delta Z} \right) \]

\[ \sigma \frac{\partial T_1^{4}}{\partial t} \left( \frac{Z}{Z} \right) = \sigma \frac{\partial T_4^{4}}{\partial t} \left( \frac{Z}{Z} \right) \]

\[ C_p \rho \frac{\partial T_1}{\partial t} = \sigma \left( T_1^{4}(Z) - T_1^{4}(Z+\Delta Z) \right) - \sigma \left( T_4^{4}(Z) - T_4^{4}(Z+\Delta Z) \right) \]

Fig. 1. The divergence of a layer in the atmosphere.

\[ \frac{\partial T_1}{\partial t} \left( \frac{Z}{Z+\Delta Z} \right) = \frac{\partial T_4}{\partial t} \left( \frac{Z}{Z+\Delta Z} \right) \]

\[ \frac{\partial T_1}{\partial t} \left( \frac{Z}{Z} \right) = \frac{\partial T_4}{\partial t} \left( \frac{Z}{Z} \right) \]

\[ C_p \rho \frac{\partial T_1}{\partial t} = \sigma \left( T_1^{4}(Z) - T_1^{4}(Z+\Delta Z) \right) - \sigma \left( T_4^{4}(Z) - T_4^{4}(Z+\Delta Z) \right) \]

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2. The double radiometer

The double radiometer measures the downward and the combined upward and downward radiation separately. From these quantities, the up and down temperatures of (1) can be evaluated at different levels in the atmosphere.

The instrument consists of two identical radiometer servo-mechanisms [9] which maintain disk-shaped detectors at air temperature with power supplied electrically. The power requirements for detector \( A \), which measures the downward radiation, and detector \( B \), which measures the combined upward and downward radiation can be expressed as follows:

\[
P_A + mcL + \sigma \varepsilon_0 AT_i^4 = \sigma \varepsilon_0 AT_a^4 \tag{2}
\]

and

\[
P_B + mcL + \sigma \varepsilon_0 AT_i^4 + \sigma \varepsilon_1 AT_i^4 = (\varepsilon_0 + \varepsilon_1)AT_a^4 \tag{3}
\]

where

\( P_A = \) power to maintain detector \( A \) at air temperature,
\( P_B = \) power to maintain detector \( B \) at air temperature,
\( m = \) mass of the detector,
\( c = \) specific heat of the detectors,
\( L = \) rate of change of air temperature with time,
\( \sigma = \) Stefan-Boltzmann constant,
\( \varepsilon_0 = \) emissivity of the top surface of both detectors,
\( \varepsilon_1 = \) emissivity of the bottom surface of detector \( B \),
\( A = \) area of the detectors,
\( T_i = \) downward equivalent radiation temperature,
\( T_a = \) upward equivalent radiation temperature, and
\( T_a = \) air temperature.

The solution of (2) and (3) for the difference of the up and down temperatures is

\[
\sigma(T_i^4 - T_a^4) = \frac{1}{\varepsilon_1 A}(P_A - P_B) + \frac{1}{\varepsilon_0 A}(P_A+mcL). \tag{4}
\]

This equation can be modified for winter atmospheric conditions by setting \( \varepsilon_1 = \varepsilon_0 \). The modified expression is

\[
\sigma(T_i^4 - T_a^4) = \frac{2P_A - P_B}{\varepsilon_0 A} + \frac{mcL}{\varepsilon_0 A}. \tag{5}
\]

The expression is further simplified when, at constant air temperature, the last term is zero. The divergence is obtained from the difference of solutions of (4) or (5) at selected points in the atmosphere.

Both radiation detectors for the double radiometer are disks 4 cm in diam and 0.5 mm thick. They are made by binding together tightly wound spirals of No. 30 constantan wire with epoxy resin. The power is supplied by passing current through the constantan wire. A layer of aluminum was evaporated onto one surface of each detector and protected by a thin coating of quartz. The other surface of the detectors was coated with flat-black Krylon paint of known emissivity. The junctions of the thermocouples in differential between the air and the detector surface, which supply the error signal to the servo system, were fastened to the blackened surface with ordinary glue.

Detector \( A \) was equipped with a sheet of aluminum foil 2 mm from the aluminized surface to obtain an effective emissivity of zero for the lower surface of the detector. Black stripes were painted on the aluminized surface of detector \( B \) to obtain the proper emissivity. The emissivity of the lower surface of detector \( B \) must be restricted to a value which will allow it to be cooled by radiating upward when a completely black object, like the black ball, is warmed above air temperature.

\footnote{Scotch Cast Resin No. 5, Minnesota Mining and Manufacturing Co.}

\footnote{Work done by Evaporated Metal Films Corp., Ithaca New York.}

Fig. 2. Detector A.

Fig. 3. Detector B.
Fig. 4. Schematic diagram of the double-radiometer gondola.
Thus, power is always required to maintain the detector at air temperature. When the radiation temperature is less than air temperature at all altitudes, as in winter, Detector B can be blackened on both sides. It will then give a direct measurement of the radiation temperature as seen by a plane-surfaced absorber. Photographs of the detectors are shown in figs. 2 and 3.

The accuracy of the instrument depends considerably upon the ambient temperature and pressure conditions. Fluctuations in the air temperature excite oscillations in the servo, and pressure changes affect the thermal time constant of the detector. The speed of the servo has been adjusted to the point where it will just follow the most rapid changes in the radiation, but the system still oscillates. The measured difference of the up and down flux under these conditions is accurate to approximately 20 per cent. It has been found that the instrument reaches equilibrium after several minutes at constant temperature and pressure. These desirable conditions are obtained by allowing the balloon bearing the instruments to float at constant altitude for one-half hour. This reduces the error to approximately 3 per cent.

3. Experimental procedure

The emissivity of the detector surfaces was determined in the laboratory wind tunnel. This was accomplished by measuring the power required to maintain the detector at air temperature while subjected to a known radiation excess. The specific heat of a detector similar to those used for the soundings was determined experimentally.

A measurement of the power radiated by the detectors during the soundings was obtained from the voltage drop across them. The voltage was measured with a transistor whose collector was connected through a rotary switch to the radiosonde transmitter. The black ball and air thermistors were also connected through the same switch. Three measurements per minute of each radiometer voltage and two measurements per minute of the black ball and air thermistors were provided. Two standard voltages were periodically applied to the measuring transistor to account for any drift in the telemetering system. A circuit diagram of the gondola is shown in fig. 4.

The apparatus was situated in the flight train so that the balloon subtended less than 1 per cent of the total solid angle seen by the detectors.

Flights 441 and 456 were step-flights. A plastic balloon whose ceiling altitude was 60 mb was inflated to give no free lift when the instruments were attached. Thus, it had just enough buoyancy to balance the weight of the instruments and 10 lb of ballast. A Darex rubber balloon was required to provide free lift. At approximately 300 mb, a pressure switch
released the rubber balloon and allowed the system, whose free lift was still zero, to float at that altitude. After floating for thirty minutes, a pre-set timer released the ballast causing the system to assume 10-lb free lift and to ascend to ceiling altitude.

4. Experimental results

Three flights were launched from the Anoka County Airport near Minneapolis, Minnesota to measure the divergence of long-wave radiation in the atmosphere at night.

The temperature profiles for these soundings are shown in figs. 5, 6, and 7. In each case, the highest temperatures represent the upward radiation, and the lowest temperatures represent the downward radiation. The air temperature and the equivalent radiation temperature are located between the upward and downward temperatures. In flights 432 and 441, the
upward temperature has been computed from the downward temperature and the corrected black-ball temperature as a check on the results. This is indicated by squares in the figures.

The radiation temperatures measured with the black ball and the radiometer agree quite well. One might expect them to differ by some geometrical factor since one instrument employs a spherical and the other employs a flat absorber. However, the measurements are almost identical.

Some interesting general characteristics of the atmosphere are apparent in the radiation-temperature profiles. In both summer soundings, there is some attenuation of the upward radiation above 250 mb, whereas in the winter sounding there is almost no attenuation above 500 mb. The downward temperatures in the summer soundings indicate the presence of radiating material above 100 mb which does not exist in the winter soundings. One might attribute this to the presence of ozone.

Fig. 8 shows the emissivity values computed from the downward radiation and the air temperature. The atmosphere is imagined to be divided into a number of layers to facilitate the computation. It is assumed that the change in the downward radiation in going from one division to the next lower division is due only to emission by the layer. The expression which describes this is

\[ T_4^s(n) - T_4^s(n + 1) = K \left[ \frac{T_a^s(n) + T_a^s(n + 1)}{2} - T_4^s(n) \right], \]

which is easily solved for \( K \), the average emissivity. The variable \( n \) in the expression denotes the division in the atmosphere.

It appears that the scaled humidity data, also shown in fig. 8, would provide a satisfactory substitute for \( K \). A simpler method of obtaining \( K \) could be useful for divergence computations from black-ball data. The scaling factor, \( p/p_0 \), is included to account for the pressure broadening of spectral lines. A value of 1000 mb has been used for \( p_0 \).

The divergence data for the soundings are shown in fig. 9. In each case, the quantity \( \sigma(T_4^s - T_4^s) \) from (4) has been plotted as a function of pressure. This is the first difference. To obtain the divergence, one must take the difference of \( \sigma(T_4^s - T_4^s) \) obtained at two separate points in the atmosphere.

The reason the data are shown in graphical form is because it is difficult to decide for which points the divergence should be computed, particularly in flights 441 and 456. Since the slope of the curves is proportional to the divergence, one can observe the trend of the curves without committing oneself to a number for the divergence. The data from flight 432 have been smoothed to facilitate the computation of some divergence values. The original data possessed the same degree of smoothness overall, that is evident above 450 mb in flights 441 and 456. The data presented in this manner provide the reader with a point of reference from which he can assess cooling rates to the trend in the curves for flights 441 and 456.

The black-ball divergence data are plotted along the right side of fig. 9. The expression from which
The least favorable case for the black ball is presented by flight 456. Below 500 mb, the radiometer shows no cooling or even slight warming, while the black ball shows a cooling rate which is increasing with altitude. Above 500 mb, the black ball shows a decrease in the cooling rate, whereas the radiometer indicates appreciable cooling. Up to 300 mb, the data appear to be contradictory, but between 300 and 30 mb both instruments indicate cooling. The 30-mb point was plotted on the 200-mb line to accentuate the difference from the 300-mb point. Between these levels, the net divergence has a value of \(-0.6C \pm 0.5C\) per day. The black ball indicated a value somewhat less than \(-0.1C\) per day for this region of the atmosphere.

Flight 441 tends to favor the black ball except for the warming at 570 mb. The warming was probably due to a thin cloud whose base was warmed by the up radiation. As the instruments approached the base of the cloud, they both indicated a decrease in the cooling rate. After passing through the cloud, both instruments again showed a cooling rate that was decreasing with altitude. Within the cloud, the radiometer indicated warming which was not shown by the black ball. It is possible that the black ball did not show the warming because it passed through the cloud very quickly. The radiometer passed through the cloud at the same rate, of course, but it would respond more rapidly to a change in the cooling rate since the detectors do not change temperature. The black ball, on the other hand, must change temperature from a value less than air temperature to a value greater than air temperature and back again to indicate the warming. The black ball approached air temperature, but before it arrived there it experienced strong cooling.

The 62-mb point is plotted on the 200-mb line. Its contrast to the 300-mb point indicates warming. The computed value is \(+0.6C \pm 0.5C\) per day. The black ball also indicated warming in this region. The value was approximately \(+0.05C\) per day.

Flight 432 presents the most favorable case for the black ball. Both instruments show cooling which decreases with altitude. No points of constant altitude are available from this flight, and hence no reliable value for the divergence can be computed for the region above 300 mb. However, below 300 mb the radiometer data are reliable and substantiate the black-ball measurements.

The behavior of the instruments is summarized in the table below. The flight numbers are listed according to whether they show the same or opposite sign for the divergence in a particular region of the atmosphere. A regional boundary has been assigned where there was some distinguishing characteristic in the radiometer data.

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\[ C_{\rho} \frac{\partial T_v(Z)}{\partial t} = 4K_{\rho}T_v^3\theta_v, \]  

(7)

where \( \theta_v \) is defined as \( \theta_v = T_v - T_w \). The temperatures for this computation were obtained from figs. 5, 6, and 7 and the emissivity values from fig. 8.

The similarity of the black-ball divergence and the first difference for the actual divergence seems to be a predominant characteristic in all of the flights. However, this is not the correlation we seek. The black-ball data actually match the first derivative of the radiometer curves as well. This is the correlation we seek.

\(^{4}\) See reference [1]
5. Conclusions

Despite the errors inherent in the experiment, the data indicate definite correlation between the measurements with the two instruments. Moreover, one of the anomalous points (570 mb, flight 441) can be explained on the basis of a thin cloud. The reason for lack of correlation below 500 mb on flight 456 is not fully understood, however, and further study on this point is necessary.

A further conclusion about the instruments is that there is very little difference in radiation temperatures measured with a spherical or disk-shaped absorber.

Two conclusions can be stated about the atmosphere. (1) It is possible for the atmosphere to be warmed by infrared radiation where the black ball is warmed above air temperature. (2) A reasonable atmospheric emissivity can be obtained from the pressure-scaled relative humidity. The latter may be useful in computing divergence values from black-ball data.

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