EVIDENCE FOR THE EXISTENCE OF THE "EMISSION LAYER" IN THE ATMOSPHERE

By R. Ananthakrishnan, F.A.Sc.

Received December 11, 1945

1. Introduction

The vertical distribution of temperature in the atmosphere is a factor of great importance in determining the processes of weather. Results of upper air soundings all over the world have shown that broadly the atmosphere can be divided into two thermally distinct zones. In the lower zone, known as the *troposphere*, the temperature decreases steadily with height at the rate of approximately 6° C./km. In the upper region, known as the *stratosphere*, the temperature remains constant or increases slightly with height. The surface of separation between the troposphere and the stratosphere is known as the *tropopause*. The tropopause is approximately 18 km. above the ground at the Equator, about 12 km. high in middle latitudes and 8 km. high at the poles. A problem of fundamental importance in Meteorology, which is as yet not completely solved, is to find out a rational physical explanation for the observed distribution of temperature in the atmosphere.

2. Solar and Terrestrial Radiation

In any attempt to answer this question, we have to start from the fundamental fact that the ultimate source of energy for all atmospheric phenomena is the solar radiation intercepted by the earth and its atmosphere. Since the mean temperature of the system (earth + atmosphere) does not show any appreciable change over long intervals of time, it follows that as much energy is sent back to outer space by this system as is received by it.

There is, however, an essential difference in the spectral characteristics of the incoming and outgoing streams of radiant energy. The solar radiation corresponds approximately to black body radiation at a temperature of 6000 °A; practically the entire energy is confined between the wave-length limits $\lambda = 0\cdot15\,\mu$ to $\lambda = 4\,\mu$ with peak intensity at $\lambda_m = 0\cdot5\,\mu$. As contrasted with this, the energy of terrestrial radiation is spread out over the band of wave-lengths from about $3\,\mu$ to $120\,\mu$ with peak intensity at about $10\,\mu$ to $15\,\mu$, corresponding to black body radiation at a temperature of 200 to 300 °A. We may, therefore, picture the earth and its atmosphere as constituting a system which is continually absorbing short-wave solar radiation and radiating it back into space in the form of long-wave heat radiation.

3. RADIATIVE EQUILIBRIUM

If the entire solar energy reaching the outer surface of the earth's atmosphere passes through without any depletion due to reflection and scattering, then every sq. cm. of the earth's surface would receive on the mean during the day and night 0·5 cal./min. Under radiative equilibrium, therefore, the same amount of energy should be radiated out by each square cm. of the earth's surface. Assuming that the surface radiates like a black body, the mean temperature T is given by:

$$\sigma T^4 = 0\cdot 5 \text{ cal./cm.}^2 \text{ min.}$$

where $\sigma = 5\cdot 73 \times 10^{-5}$ erg. cm.$^{-2}$ deg.$^{-4}$·sec.$^{-1}$ (Stefan's constant).

This equation when solved for T gives

$$T = 279 \text{ °A} = +6\text{° C.} \qquad (1)$$

We know, however, that about 40% of the incoming solar energy is directly returned to space due to reflection, scattering, etc. If it is assumed that the remaining 60% is absorbed at the surface of the earth, then the corresponding equation for radiative equilibrium becomes

$$\sigma T^4 = 0\cdot 3 \text{ cal./cm.}^2\cdot\text{min.}$$

which gives $$T = 246 \text{ °A} = -27\text{° C.} \qquad (2)$$

The observed mean temperature of the earth's surface is however + 14° C., *i.e.*, it is higher than either of the above values.

4. "GLASS HOUSE EFFECT" OF THE ATMOSPHERE

What is the reason for this high surface temperature of the earth? In order to understand this, we have to consider the assumptions on which the calculations in the preceding section were based. We tacitly assumed that the atmosphere is perfectly transparent to both solar and terrestrial radiation so that the incoming and outgoing streams of radiant energy pass through the atmosphere without any attenuation. We know, however, that while the atmosphere is largely transparent to short-wave solar radiation, it is highly opaque to wave-lengths in the range of terrestrial radiation, because the water vapour and CO_2 always present in the atmosphere possess intense absorption bands in this spectral region. Consequently, the greater part of the heat radiation from the earth's surface is absorbed and trapped by the water vapour and CO_2 in the lowest layers of the atmosphere. These constituents in their turn re-radiate energy over the same wave-lengths at which they absorb, so that a downward stream of radiant energy is directed toward the surface of the earth from the lower layers of the atmosphere (Gegenstrahlung). The net loss of energy from the surface of the earth (Ausstrahlung) is now less than before; it is equal to the difference between σT^4 and the Gegenstrahlung. Thus the effect of water vapour and CO_2 is to reduce the loss of heat from the surface of the earth or to increase the surface temperature. This is known as the "Glass House Effect" of the atmosphere.

5. Radiative Loss of Heat from the Atmosphere and Albrecht's Emission Layer

With an atmosphere which absorbs and radiates like a black body, the net loss of heat from the earth's surface would be reduced practically to zero, because all the radiation sent out from the earth will be absorbed in the lowermost layers which have practically the same temperature as the earth and would therefore send back an equal amount of radiation towards the earth. However, the water vapour and CO_2 which constitute the major absorbing and radiating constituents of the lower atmosphere do not absorb all wavelengths in the range of terrestrial radiation. As was first shown by Simpson, the absorption spectrum of water vapour in this spectral region can be broadly divided into three categories:—

(1) The spectral band $8\frac{1}{2}\mu$ to 11μ in which water vapour is completely transparent.

(2) The bands 7μ to $8\frac{1}{2}\mu$ and 11μ to 14μ in which water vapour is semi-transparent.

(3) Wave lengths $< 7\mu$ and $> 14\mu$ for which water vapour is so highly opaque that a small amount (according to Simpson 0·3 mm. of precipitable water) is sufficient to absorb completely all radiation.

Out of the total energy σT^4 radiated from the surface of the earth, the entire amount comprised in the spectral band (1) and a portion of the energy in the spectral range (2) are thus directly lost to outer space. It is estimated that out of the 60% incoming solar energy absorbed by the earth and the atmosphere, about 10% only is disposed of in this way. The remaining 50% of long-wave heat radiation returned to space is contributed by the atmosphere.

From which part of the atmosphere does this large amount of heat radiation which is being continually lost to outer space originate? This is a most important problem in the theory of atmospheric heat radiation. We have seen that the principal absorbing and radiating constituents of the lower atmosphere are water vapour and to a lesser extent CO_2. These constituents, however, send out radiation over the same wave-lengths at which they absorb intensely. If we now picture the atmosphere as being divided into a number of layers each of which contains the optimum quantity of the absorbing constituents to intercept completely the radiation from the layer below it, then, it is easy to see that outward radiation to space can begin only at such a height above which the amount of water vapour and CO_2 present is insufficient to absorb completely all the radiant energy arriving from below.

Simpson assumed that the stratosphere contains enough water vapour to absorb all the radiation coming from the troposphere and that outward radiation to space from the atmosphere originates only from the stratosphere. Later work has, however, shown that Simpson's assumption requires revision.

From a careful study of the absorption and emission spectrum of water vapour, F. Albrecht came to the conclusion that the greater part of the heat radiation sent out into space from the earth's atmosphere has its origin in the upper troposphere and that this radiation passes through the stratosphere without appreciable depletion. According to Albrecht, radiation to outer space from a cloud-free atmosphere is mostly from a layer of about 3 to 4 km. thickness in the upper troposphere, which he designated as the "*Emission Layer*". The radiation from the emission layer is independent of geographical latitude or of the time of the year and is approximately equal to the selective radiation of water vapour and CO_2 at a temperature of $-50°$ C.

The location of the emission layer in the atmosphere is determined by two important considerations, *viz.*,

(1) It contains an optimum amount of water vapour and CO_2 (the constituents that give rise to emission).

(2) The amount of water vapour and CO_2 above the layer is so small that the radiation from the emission layer passes through without appreciable attenuation.

As the emission layer is a region which is losing heat throughout day and night, it is also a part of the atmosphere which is getting continually cooled due to this heat loss.

According to Albrecht's estimates, the emission layer is located at such a height that the water vapour content at its base is approximately $0 \cdot 1$ gm./m^3 and its top $\cdot 01$ gm./m^3. Consequently, the height of the emission layer varies with the temperature and humidity content of the atmosphere. It has been estimated by Albrecht that when the atmosphere is hot and humid, the emission layer should lie roughly between the levels corresponding to 233 °A and 213 °A; when the atmosphere is comparatively dry, the emission layer should extend from 243 °A to 223 °A.

More recent researches on the absorption spectrum of water vapour have shown that the absorption coefficients given by the earlier workers are far too high and hence would necessitate a much higher value than what Simpson assumed for the critical quantity of precipitable water which constitutes a " black body " for the range of wave-lengths over which water vapour shows marked absorption. Brunt has pointed out that this would not essentially modify the arguments of Simpson and Albrecht although the base of the emission layer would be lower and its thickness more than what was estimated by Albrecht.

6. EMISSION LAYER AND TROPOPAUSE

According to Albrecht, the top of the emission layer marks the upper limit of the troposphere in polar and temperate latitudes. In the tropics, however, on account of the strong penetrative convection from below, brought about mainly through the agency of water vapour, the tropopause is carried a few kilometres above the top of the emission layer. As a result of this, the temperature of the upper troposphere (above the top of the emission layer and below the tropopause) in the tropics is *lowered* below what it would normally have been as a result of purely radiative processes. Hence, in radiative heat exchange with the lower layers of the stratosphere the upper levels of the tropical troposphere absorb more heat than they radiate out. This is supposed to be the reason (perhaps only one of the reasons) for the sharp inversion at the tropopause and the rapid increase of temperature in the first few kilometres above that in the tropical stratosphere, a feature which is not observed in higher latitudes where the lower stratosphere is practically an isothermal region.

7. DISTRIBUTION OF HEAT AND COLD SOURCES IN THE ATMOSPHERE

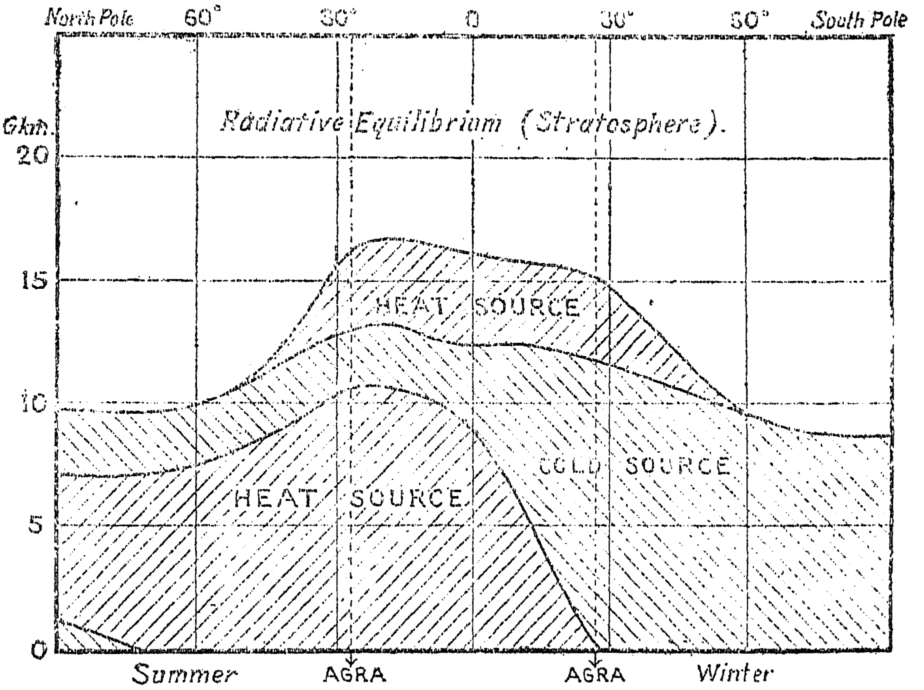
While the long-wave outgoing radiation from the atmosphere causes a perpetual cooling of the upper troposphere, practically all the addition of heat resulting from the absorption of short-wave solar radiation takes place essentially at the surface of the earth and in the lower layers near the surface. Thus vertical temperature gradients are set up in the troposphere which give rise to vertical displacements of air masses when the gradients exceed the limits of stability. Consequently, in spite of the continuous loss of heat from the top and addition of heat at the bottom, a dynamical equilibrium with certain limiting temperatures is established.

If we consider the annual mean heat balance of the system (earth + atmosphere), then according to Albrecht's calculations the incoming energy exceeds the outgoing up to latitude $37\frac{1}{2}°$, while at higher latitudes the reverse conditions obtain. As is well known, it is this peculiar latitudinal distribution of incoming and outgoing energy that brings about the general circulation of the atmosphere.

Bjerknes has divided the troposphere into regions where there is a net gain of heat or a net loss of heat. The former are called heat sources and the latter cold sources. The principal cold source in the atmosphere is Albrecht's emission layer which is continually sending out heat energy into outer space. The principal heat source is the lower troposphere in the tropics and the adjoining temperate latitudes which gains a net excess of energy in radiative heat exchange with the earth's surface and also in the form of latent heat of condensation. Besides this, there is a secondary heat source which is the region comprised between the top of Albrecht's emission layer and the tropopause over the tropics and adjoining temperate latitudes. This is a region which is cooled by convection below its radiative equilibrium temperature and as such gets a net excess of heat by radiative exchange with the lower layers of the stratosphere.

8. SEASONAL VARIATION OF HEAT AND COLD SOURCES OVER THE NORTHERN HEMISPHERE

If we consider the vertical distribution of heat and cold sources over the northern hemisphere (Fig. 1), there is a striking difference in the conditions which obtain in the summer and in the winter seasons. In the *northern*



PROBABLE SPATIAL DISTRIBUTION OF HEAT AND COLD SOURCES IN THE ATMOSPHER IN JUNE.

(After Bjerknes)

FIG. 1

summer, practically the whole of the lower troposphere is a heat source; the middle or the upper troposphere (Albrecht's emission layer) forms the cold source. Above this lies the secondary heat source extending from the Equator up to and somewhat beyond 30° N. In the *northern winter*, the lower heat source is displaced towards the southern hemisphere so that the entire troposphere (limited by the top of Albrecht's emission layer) over polar and temperate latitudes is a cold source suffering a continual loss of heat energy. Above the top of this is a feeble heat source which stretches over a part of the temperate latitudes and is in fact an extension of the secondary heat source over the tropics brought about by meridional advection of air.

9. EXPECTED SEASONAL VARIATIONS IN THE THERMAL STRUCTURE OF THE ATMOSPHERE OVER TEMPERATE LATITUDES ADJOINING THE TROPICS

The considerations of the preceding section would lead us to expect striking seasonal variations in the thermal structure of the atmosphere over a place in the temperate latitudes adjoining the tropics. Such observed variations in their turn can also be regarded as a proof of the general validity of the theoretical considerations outlined in the preceding sections and hence of the existence of the emission layer in the upper troposphere.

What are the changes that we should expect in the thermal structure of the atmosphere over a place such as Agra (lat. 27° 08′: long. 78° 01′) between summer (July) and winter (January)?

Let us first consider the location of the cold source (Albrecht's emission layer) in these two months (see Fig. 1). In July, the atmosphere is hot and humid and the emission layer (following Albrecht) may be taken to be between 11 to 14 gkm. In winter, the entire troposphere below the emission layer is a cold source; the emission layer itself should be between 8 and 11 km. according to the temperate limits given by Albrecht.

In summer, the lower troposphere is a powerful heat source and the condensation of water vapour is by far the most important agency controlling the lapse-rates in the middle and upper troposphere. The lapse-rates at these levels would, therefore, follow the saturation adiabat which, however, is practically parallel to the dry adiabat under the conditions prevailing in the upper troposphere. Within the emission layer itself, there is a continual cooling due to radiation, so that as a result of addition of heat at the bottom and loss of heat from the top there should be a marked tendency for super-adiabatic lapse-rates at these levels. Above the top of the emission layer, convection and radiation work in opposite directions, the former tending to set up dry adiabatic lapse-rate while the latter tends to establish isothermal conditions. Consequently a rapid decrease of lapse-rate with height should be noticed in the column above the top of the emission layer and below the tropopause. The inversion at the tropopause would be very pronounced and a rapid rise of temperature with height should be the feature in the first few kilometres of the lower stratosphere.

In the winter months, the entire troposphere below the top of the emission layer is a cold source undergoing continual cooling due to radiation. The cooling increases with height and attains a maximum value within the emission layer. The vertical distribution of lapse-rate should thus correspond to what would be expected in an air column which is continually cooled at the top; that is, the highest lapse-rates should occur in and below the emission layer. Above the top of the emission layer, radiative processes alone would set up isothermal conditions. However, meridional movement of air from lower towards higher latitudes transports the characteristics of the tropical tropopause to the temperate latitudes in a less pronounced form. We should thus expect a "composite" type of tropopause over temperate latitudes, the transition from the troposphere to the stratosphere occurring in two stages. The lower transition will correspond to the top of the emission layer, while the upper transition will correspond to the tropopause over the tropics. However, because of the absence of penetrative convection from below, the control by radiation will be more pronounced than in the tropics so that the lapse-rates and upper inversion above the top of the emission layer will be less conspicuous than in the tropics.

In this connection it is interesting to recall a scheme of air circulation between the troposphere and the stratosphere which was suggested by Refsdal some years ago. This is based on the work of Albrecht as well as on the concept originally put forth by Palmén that the tropopause should be regarded as a layer of transition which can dissolve at one level and reappear at a new level in the atmosphere depending upon dynamic as well as radiative conditions. In the temperate latitudes, the tropopause is dynamically sucked down in association with depressions and reforms at its original level when the depression activity has ceased. In this process, therefore, air from the stratosphere is transferred to the troposphere. According to Refsdal, the compensating transport of air from the troposphere to the stratosphere takes place in the tropics where the tropopause is carried above the top of the emission layer by convection, and consequently is constantly striving to build itself at a lower level under the influence of radiation.

From what we have discussed in the preceding, it would appear that the meridional movement of air from lower towards higher latitudes in the upper troposphere furnishes the necessary mechanism for the transport of air from the troposphere to the stratosphere; for, in the absence of penetrative convection from below at the higher latitudes, the high vertical temperature gradients which prevail in the upper levels of the tropical troposphere can no longer be maintained as the air moves over to the higher latitudes. The lapse-rates would, therefore, progressively decrease in the meridionally advancing air column until finally it gets merged with the stratosphere in the higher latitudes. The "composite" tropopause encountered in temperate latitudes appears to mark an intermediate stage in the transition of tropical tropospheric air into stratospheric air of the temperate latitudes.

10. THERMAL STRUCTURE OF THE ATMOSPHERE OVER AGRA

A detailed study of the thermal structure of the atmosphere over Agra based on the results of over 500 sounding balloon ascents shows that the observed seasonal variations in the thermal structure of the atmosphere are quite in conformity with what should be expected in the light of Albrecht's work. A detailed account of the investigation is being published elsewhere, Some of the major features brought out by the study might, however, be summarised here:—

(1) In the month of July, the observed lapse-rates in the middle and upper troposphere over Agra practically follow the saturation adiabatic; super-adiabatic lapse-rates are frequently encountered between 12 and 14 gkm. Above 14 gkm., the lapse-rate begins to decrease and changes over into an inversion at about 18 gkm.

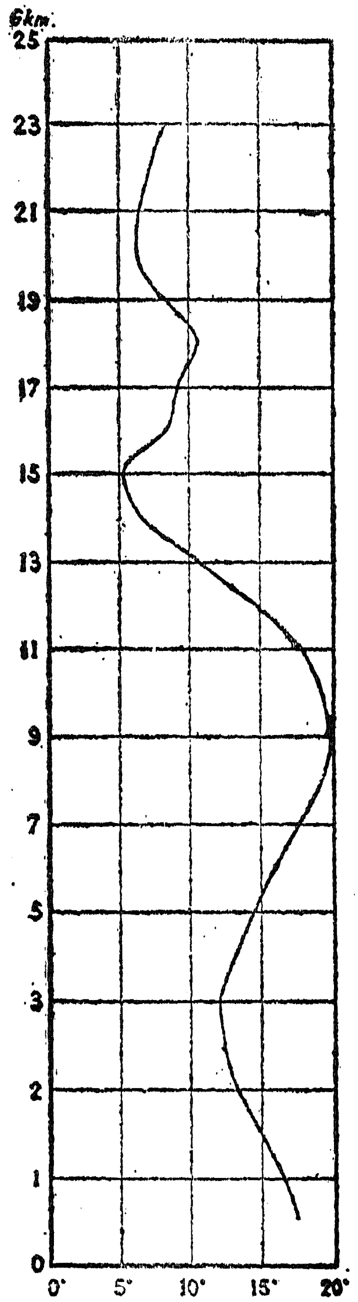
(2) Following the retreat of the monsoon in September, there is a decrease of lapse-rate in the upper troposphere and an increase in the middle troposphere over Agra.

(3) A sudden decrease of lapse-rate at about 11 gkm. is noticed in a more or less conspicuous form during all the winter months.

(4) The highest lapse-rates in the winter months are noticed between 7 and 11 gkm.

(5) In the winter months, lapse-rates above 11 gkm. are generally feeble and gradually change over to an inversion at about 17 gkm.

(6) The annual range of temperature in the atmosphere over Agra shows two maxima, one at about 9 gkm. and another at about 18 gkm. (see Fig. 2). Starting with the thermal conditions obtaining in summer



ANNUAL RANGE OF TEMPERATURE OVER AGRA

FIG. 2

(July), the lower maximum can be interpreted as the level of maximum cooling in winter (centre of gravity of the emission layer in this season). The upper maximum corresponds to the summer tropopause and is the region where the greatest fall of temperature below that corresponding to radiative equilibrium has been brought about by convection from below. It follows that with decreasing control by convection and increasing control by radiation (transition from the monsoon to winter conditions), there should be a rise of temperature at all levels in the upper troposphere (above the top of the emission layer) and lower stratosphere, the rise of temperature being a maximum at the level of the summer tropopause.

All these facts lend strong evidence for the existence of the "Emission Layer" in the upper troposphere and the seasonal variation of its altitude depending upon the moisture content of the atmosphere.

11. EFFECT OF OZONE ABSORPTION ON THE TEMPERATURE OF THE LOWER STRATOSPHERE

Above the level of the tropopause, vertical transport of heat by convection is not possible, because of the extreme stability of the thermal stratification. Hence the temperature of the lower stratosphere should be conditioned mainly by the balance between absorbed and emitted radiation. In addition to the part played by water vapour and CO_2 at these levels, the absorption and emission by ozone whose average height has been estimated to be between 20 and 25 km. has no doubt to be taken into account in considering the radiative equilibrium of the lower stratosphere. Ozone has a strong absorption band between $0 \cdot 22\,\mu$ and $0 \cdot 33\,\mu$ wherein the incoming solar radiation has appreciable energy. Probably about 5% of the incoming short-wave radiation is absorbed by ozone. Again, ozone has another absorption band in the infra-red at $9 \cdot 5\,\mu$. It is significant that this band is close to the wave-length of maximum energy in terrestrial radiation, while water vapour is transparent for radiation of the same wave-length. A detailed discussion of radiative phenomena in the stratosphere is unfortunately not yet possible because of gaps in our existing knowledge regarding the absorption spectrum of water vapour under stratosphereic conditions as well as of the water vapour content of the stratosphere.

SUMMARY

The theory of radiative equilibrium demands that on the average the total amount of energy absorbed by the earth and its atmosphere in the form of short-wave solar radiation should be exactly equal to the total amount of energy given back to space in the form of long-wave heat radiation. From a study of the absorbing and radiating properties of the atmosphere, F. Albrecht arrived at the fundamental result that the major contribution to the long-wave heat radiation into outer space originates from a layer of some three to four kilometres thickness in the upper troposphere, which he designates as the "*Emission Layer*". The emission layer is thus a portion of the upper atmosphere which is continually cooling due to radiative loss of heat. The height of the emission layer is a function of the water vapour content of the atmosphere; it is more when the atmosphere is hot and humid and less when the atmosphere is cold and dry.

The author has made a detailed study of the thermal structure of the atmosphere over Agra based on the results of sounding balloon ascents over a period of ten years. A number of interesting features find a ready explanation on the assumption that the emission layer over Agra is located approximately between 11 and 14 gkm. in the monsoon months and between 8 and 11 gkm. during the remaining months,—an assumption in conformity with Albrecht's work. The observed seasonal variations in the thermal structure of the atmosphere over Agra thus lend strong evidence for the existence of the emission layer in the atmosphere and the variation of its altitude depending upon the moisture content of the atmosphere.

REFERENCES

1. G. C. Simpson .. *Mem. Roy. Met. Soc.*, 1928, **3**, No. 21.
2. F. Albrecht .. *Met. Zeit.*, 1931, **48**, 57.
3. V. Bjerknes and others .. *Physikalische Hydrodynamik*, 1933, pp. 663–68.
4. D. Brunt .. *Physical and Dynamical Meteorology*, 1939.
5. ——— .. *Q. J. Roy. Met. Soc.*, 1940, **66**, (Supplement), 34.
6. G. M. B. Dobson .. *Ibid.*, 1942, **68**, 202.
7. A. Refsdal .. *Geophys. Publik.*, 1932, **9**, No. 12.
8. R. Ananthakrishnan .. *On the Thermal Structure of the Atmosphere over Agra* (under publication).

52-46. Printed at The Bangalore Press, Bangalore City, by G. Srinivasa Rao, Superintendent
and Published by The Indian Academy of Sciences, Bangalore.