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Tropical Thunderstorms and Radar Echoes*

S. MULL, H. MITRA and S. M. KULSHRESTHA

Meteorological Office, New Delhi

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ABSTRACT. The paper classifies different types of tropical thunderstorms and describes the mechanism of formation of these types. An attempt is made to identify these types by means of echoes observed on scopes of weather radars through various stages of their development.

1. Introduction

Of all the phenomena of the atmosphere there is none, particularly in the tropics, that surpasses a thunderstorm as an example of the fury and violence which nature exhibits when she seeks to restore a state of balance which due to some reason, has been temporarily upset. It is a terror to those who are in air principally because of the violent vertical movements and the strong squalls associated with it. In view of the above, study of thunderstorms has attracted particular attention of meteorologists, and although a number of papers discussing them have appeared in different journals, still very little is understood about their structure or the mechanism which brings about the culmination of a cumulonimbus cloud into a full-fledged thunderstorm and the circulation resulting therefrom. Recently, however, the application of the radar technique to the science of meteorology has placed at the disposal of the meteorologist, a tool, by which not only can he forewarn the aviators of the presence of these hazards but can also get fresh insight into the complex structure associated with them. Realising, therefore, the importance of such studies, the India Meteorological Department obtained in the year 1950-51, a few airborne radars for installation at New Delhi and Poona. The equipment at New Delhi consisted of one 3-cm radar, type AN/APQ-13 and one 10-cm radar type SCR-717/C and that at Poona of one 10-cm unit, SCR-717/C. With the help of these radars, types of precipitation echoes, that are observed in the tropics, were studied and classified.

Recently, a more powerful radar, type AN/CPS-9 was installed at Safdarjung Aerodrome and has been in operation for the last three years. In the year 1955, one Decca type 41 Storm Warning Radar was installed at the Forecasting Office at Dum Dum airport, which was replaced by a more powerful radar type NMD-451/A in 1958. Although this radar is operated mainly for the issue of short range forecasts to pilots, radar studies of important meteorological phenomena like Nor'westers, thunderstorms etc are also made, whenever important weather situations are noticed on the scope. An attempt has been made in the present paper to confirm some of the previous conclusions regarding the structure of thunderstorms and to suggest a method, based on the records of self-recording instruments and the radar photographs, by which the different types of thunderstorms can be distinguished from each other.

2. Classification of thunderstorms

A study of synoptic weather maps in India on days of thunderstorms shows

*Paper presented at the Symposium on 'Thunderstorms' held at New Delhi on 9-11 March 1960 that they can be conveniently classified under three main divisions—

(*i*) Those which are associated with the out-break of cold air at the surface, or in other words, 'Cold Front Thunderstorms'.

(*ii*) Those which occur in the same air mass or in other words, 'Heat Thunderstorms'.

(*iii*) Those which occur simultaneously over a large area and are associated with a surface of discontinuity, with dry air above and moist air below, at some higher level. These thunderstorms are characterised by a very rapid and instantaneous vertical growth and shooting up, with explosive violence, of a towering cumulus when its head reaches the surface of separation. These are the pre-monsoon thunderstorms, popularly known as 'Nor'westers' or *Kal Baisakhis* in Bengal and *Andhis* in NW India.

While the cold front thunderstorms, which are associated with a pressure rise and temperature fall of the persistent type (Fig. 1) at the surface, can very easily be distinguished from the other two types (Fig. 2), the same is not the case with regard to the remaining two. As has been shown by Mull and Rao (1950a), the air mass thunderstorms, even though they develop in the same air mass, show variations of meteorological elements at the surface which are hardly different from the customary signs associated with high level discontinuity thunderstorms *i.e.*, 'Nor'-westers' or '*Andhis*'.

It is now proposed to review briefly the present position regarding the origin, development and structure of the various types and to show that the radar technique provides a very useful information which helps us in distinguishing one type of thunderstorm from another and in confirming the conclusion arrived at theoretically about the origin of downdrafts and circulation in them.

(*i*) *Cold front thunderstorms*—The most striking and easily understood of all radar-scope PPI photographs are those of echoes from the squall associated with an active cold front. As the physical processes which give rise to cold front and the associated thunderstorms are so well known, it is not necessary to repeat the same here.

In Figs. 3 to 11 are reproduced the radar echo photographs when a cold front passed over New Delhi on 28/29 January 1959. It will be seen that—

(1) As soon as the cold front, noticed in weather map at 1730 IST on 28 January 1959 (not reproduced here), comes within the detectable range of the radar, echoes from the upper portion of *Cb* clouds appear on the PPI as a long, rarely continuous and generally a very narrow band due to finite beam width and consequent poor discrimination by the set (Fig. 3).

(2) As the cold front comes nearer, the band of echoes appears to be composed of a large number of cells (Fig. 4) often with little separation (Fig. 5) which break up and reform and change constantly in shape as they pass across the scope (Fig. 6).

(3) When the front is very near the station, the radar echoes again lose their cellular structure (Figs. 7 and 9) and show the same only when receiver gain is adjusted to remove weaker echoes caused by drops of smaller sizes.

The individual cells on RHI scope show typical cellular structure representing cores of strong vertical motion associated with *Cu* or *Cb* cloud at the leading edge of the front (Figs. 8 and 10).

(4) This trend continues until the front passes over the station when the echoes from the more distant storms become weak because of rain attenuation and the precipitation appears to be almost evenly distributed around the radar for a distance of many miles (Fig. 11).

(5) After the passage of the storm over the station, the above sequence of events are reversed until the front becomes diffused, weak or goes beyond the range of detection of radar.

(6) The apparent length of the front shows an increase as the front approaches the station due to decrease in the effect of rain attenuation except when it is over the station when due to complete blockade by heavy rain, the echoes from the outer portion of the front get completely masked (Figs. 6 and 7).

(7) The depth of the cold front echoes varies greatly with the distance as well as activity. The depth shows an increase with increased activity and decreasing distance from the station (Figs. 4 and 7).

(8) Sometimes the frontal system of thunderstorm is preceded by another prefrontal squall line type of thunderstorm of comparatively weak activity, parallel to the parent system. This appears on PPI by a narrow band of echoes parallel to the main front (Figs. 9 and 11). It will be seen that in the first case the prefrontal storm activity is about 60 miles ahead of the main front.

(*ii*) *Air mass thunderstorms*—These thunderstorms occur well within an air mass unaffected by activity at a surface of discontinuity. As they are initiated by convective currents caused by either surface heating or by the movement of air over a warmer surface, they may be said to be produced thermally. There are usually five stages of cloud development for such a thunderstorm. In the first stage, on account of the setting up of a nearly dry adiabatic temperature gradient either due to local heating or due to the transport of air over warmer regions, small areas of ascending currents are produced in the atmosphere which ultimately result in the formation of a cumulus above the condensation level.

In the second stage, the convection currents in the cumulus are accelerated on account of the release of latent heat and one or more of them show rapid development. In both these stages, as the compensating downward current is relatively widespread compared to the concentrated core of rising air, the downdraft is comparatively weak and the cloud air is less dense than the environment (Fig. 12).

The next stage in the growth of the cloud is the beginning of cumulonimbus stage when with further ascent, the top portion of cloud commences to be denser than the environment (Fig. 13). Mull and Rao (1949) have shown that at this stage also as in the two previous ones, there is a high pressure zone just at the top of the cloud but due to higher density of cloud (over the environment), the high pressure intensifies below the top upto the level where the density in the cloud is the same as that of the environment. As a result of this high pressure aloft, the high pressure zone extends down to some level into that portion of the cloud which is less dense than the environment. Below that level, the low pressure zone builds up. The convergence in the low pressure zone is greater than the divergence in the high pressure portion of the cloud and hence the cloud continues to grow. The cloud also spreads out in the high pressure zone, unlike the previous stage, as the higher pressure is steadily maintained.

The fourth stage in the growth of the cloud is the one when the cloud attains the stage of fully grown cumulonimbus (Fig. 14). This stage is reached when the pressure right at the top of the cloud becomes the same in the environment and the cloud no longer grows. A high pressure zone builds up below the top and is most intense at the level, where the cloud air comes to have the same density as the environment. Below that, the cloud air is less dense than the environment and the high pressure zone first diminishes in intensity and finally changes into low pressure zone which attains the maximum intensity at the ground. The convergence in the low pressure zone below and the divergence in the high pressure zone aloft are in this stage equal so that there is no further growth of the cloud. A stage of dynamic equilibrium is thus reached, when cumulonimbus with its fully grown anvil can maintain itself without any further growth or decay for hours together, and does not always culminate into a full-fledged thunderstorm as the mechanism for the production of local concentrated cooling at higher levels does not always exist in these clouds.

In the fifth stage of development, the cloud culminates into a full fledged thunderstorm giving rise to a rapid downdraft and the associated variations of meteorological elements at the surface. Mull and Rao (1950 b) have discussed this stage in detail and have shown that

(1) Such of the air mass cumulonimbus clouds in which only ice crystals are present above the freezing level will not culminate into a thunderstorm.

(2) Air mass cumulonimbus in which supercooled water drops exist above the freezing level will culminate into a thunderstorm only, if

(*a*) There is an accumulation of water in liquid and solid phase in the levels of supercooling so that the amount of liquid water (per kgm of dry air) contained in supercooled layers is greater than the amount in the layers above having only the solid phase.

(*b*) The level of accumulation is just above the freezing level and not very much above it, so that when as a result of sudden congelation of supercooled water drops, turbulence similar to the one observed in a thin unstable layer of fluid develops at the boundary between the layer of supercooled water drops and the air aloft, ice crystals can be carried to the non-freezing levels, resulting in the local concentrated and decided cooling of the environment there and the ultimate culmination of the *Cb* into a full fledged thunderstorm with a downdraft. If the amount of water content in the downdraft is not enough to keep the humidity 100 per cent, the cells in the cloud will develop craters in the zone of a downdraft and holes like the one observed at Kano will appear at the base of the cloud.

One would now expect to find the following characteristics in radar photographs of a typical air mass thunderstorm—

(*i*) Scattered oval shaped echoes with fairly clear cut edges of convection type on the PPI scope from cloud cells occurring over a large area growing and intensifying with time as *Cu* cells grow into towering cumulus.

(*ii*) Echoes on RHI scope showing large vertical extent, roughly cylindrical in shape consisting of a single column but at other times of two or more columns when associated with an extensive cumulonimbus.

(*iii*) Echoes on RHI scope at times showing widening at the tops indicating the spreading out of the vertical currents.

(*iv*) An increase in echo intensity in a narrow altitude range in the vicinity of the zero degree isotherm (usually designated as melting band) due to the concentration of supercooled water drops in the level of accumulation.

(*v*) Cellular structure in the bright band indicating the presence of turbulence of the type observed in a thin unstable layer of fluid.

(*vi*) Echoes on RHI scope showing type of precipitation streaks starting from melting band downwards, and

(*vii*) Holes in the photographs of precipitation echoes on PPI.

As the radars in operation in India are primarily to be used as meteorological aid to the forecaster in the issue of aviation and other warnings, it is not possible to reproduce a series of radar pictures of a single cloud cell at the various stages of development which will show all the above characteristics. In order to be able to do so, it is necessary to have radar photographs the same cloud (both PPI and RHI) taken continuously at shorter intervals during the various stages of development, growth and dissipation. Examples selected from a large number of photographs presented here, however, give enough evidence of the existence of the above characteristics.

Figs. 15—18 show the progressive growth of air mass type thunderstorms on the PPI at New Delhi on 7 July 1958. From these pictures, it is seen that the echoes in the western half are mostly of a cellular nature with fairly smooth and well defined boundaries typical of columnar type of cells associated with convection clouds. The photographs also very clearly illustrate the growth of these cells in size as well as in intensity with time as the cumulus cloud with the progress of the day grows into towering cumulus and finally to *Cb*.

Figs. 19-26 show the vertical structure and the progressive growth of the echoes of the air mass thunderstorms on RHI. For sake of convenience of following the development and structure of the same cell in various directions, the RHI pictures taken in the same direction have been grouped together. Five such series have been reproduced representing directions 080°, 274°, 240°, 230° and 056°. It will be seen that the echoes on the RHI are roughly cylindrical in shape and of large vertical extent consisting of a single column (Figs. 22 and 23) or two or more columns (Figs. 21, 24 and 26). While the first one represents a simple *Cb* cell, the latter is associated with extensive *Cb*. Some of the echoes are also characterised by the widening at the top indicating the spreading out of the vertical currents (Fig. 25). Although the radar echo photographs with full gain do not show any variation of echo intensity with height (Figs. 21, 22, 23, 24 and 26), the photographs with reduced gain are characterised by an increase in echo intensity in a narrow altitude roughly in the vicinity of the zero isotherm confirming the accumulation of supercooled water drops at this level (Figs. 19, 20, 22 and 25). The Benard type cellular structure of this bright band in some of the photographs also confirms the mechanism postulated by Mull and Rao for production of turbulence in this layer (Figs. 19 and 20). The echoes showing cellular type of precipitation streaks starting from this melting band downwards is also visible in Figs. 19, 20 and 25.

Fig. 27 shows the circular holes in the radar echoes of dissipating cells, which confirms the conclusion drawn by Mull and Rao referred to above.

That the melting band observed in the above cases is associated with convective clouds and not with stratiform clouds which appear during the dissipating stages of *Cb* clouds associated with cold front or high level discontinuity, is quite apparent from the convective types of echoes in PPI and RHI photographs. Also the fact that the melting band in these cases is actually a confirmation of the level of accumulation and occurs in the earlier stages of the development of *Cb* cloud is evident from the cellular nature it shows in the RHI photographs with reduced gain.

(*iii*) *High level discontinuity thunderstorms*—These are the thunderstorms of the Nor'-wester or the *Andhi* type discussed by Desai and Mull (1938) and are not the frontal thunderstorms associated with either cold or warm front. As mentioned earlier such storms are associated with a high level surface of discontinuity with warm and dry air above cold and moist air. The three stages in the development of such thunderstorms are described below—

In the first stage, on account of the effect of insolation, convection currents are set up irregularly and result in the formation of cumulus clouds as soon as they reach the condensation level in a way similar to that of the heat thunderstorms (Fig. 28).

In the second stage, with the advance of the day and greater heating, these currents increase progressively and go higher and higher resulting in the development of towering cumulus here and there; but in this stage the cloud tops are still below the surface of discontinuity (Fig. 29).

In the third stage, on account of the greater heating, ascending currents become so strong that the top of the towering cumulus reaches the surface of discontinuity. When this happens, the surface of discontinuity which was characterised by an inversion earlier gets completely wiped off and a layer with marked instability is set up with the consequence that the cumulus heads as soon as they reach this level shoot up with explosive violence causing a rapid downflow of the upper air thereby generating a violent type of thunderstorm. The structure of the cloud and the stream line motion inside this is shown in Figs. 30 and 31.

The main features of this type of formation are—

1. The growth of instability in the earlier stages is gradual and takes place at the under-surface; the cloud development, therefore, initially is gradual and occurs in a way similar to that of the heat type thunderstorms.

2. When, however, the cloud tops reach the boundary layer between the moist and dry air, the dry air which was relatively warmer than the moist air initially, suddenly becomes relatively cooler with reference to the moist air below and hence the development of instability is sudden and occurs at the top surface of the moist column.

3. The main difference, therefore, between the physical processes leading to the formation of these thunderstorms and the heat thunderstorms is that whereas in the case of heat thunderstorms, the local instability is produced as a result of congelation of supercooled water drops, in the case of Nor'westers or *Andhis*, the agency of insolation produces sudden instability at the top of the column thus influencing the growth from the top surface of the moist column.

4. Whereas in the case of heat thunderstorms, the local cooling required for descending current is produced at a fairly advanced stage of *Cb* formation and is in the vicinity of level of accumulation, *i.e.*, freezing level; in the second case the intense local cooling is produced at the interface between the upper warm and dry air and lower moist and cold air even at an early stage of the cumulus growth and being very sudden is responsible for the sudden growth of the cumulonimbus and the simultaneous descending currents.

5. As the trigger for the initiation of the downdraft in both types of thunderstorms is the same, *i.e.*, intense local cooling, the variation of pressure, temperature and wind associated with their passage is similar in both cases.

6. As the height of the upper air discontinuity is roughly about 1·5 to 2 km a.s.l., the intense local cooling required for descending current is very much below the freezing level.

7. As the breakdown of instability takes place very suddenly and near the head of the towering cumulus, the individual cloud will show only one cell with descending centre and not a number of cells as in the case of air mass thunderstorms.

It has been observed that at times the displacement of the warm and moist air at the surface by cold air from the downdraft gives rise to a series of thunderstorms along a line which resemble to some extent those occurring on a cold front.

Assuming that the hypothesis given above is correct, one would normally expect the following characteristics in radar echoes from high level discontinuity thunderstorms—

(1) Scattered echoes on the PPI from cloud cells occurring over a large area, which

will grow and intensify with time, as the cumulus cells grow into towering cumulus.

(2) Column type precipitation echoes on the RHI, which show growth of precipitation from low levels upwards; and little change in the echo intensity with height.

(3) Complete absence of the melting band type of echo on the RHI due to the non-existence of level of accumulation near the freezing level at any stage.

(4) Sudden and quick vertical development of the echoes on the RHI due to the sudden growth of the towering cumulus to cumulonimbus and decrease both in intensity and vertical thickness of the echoes thereafter due to culmination in a thunderstorm.

(5) Type of radar echoes similar to those described under cold front in those cases where the downdraft gives rise to squalls along a line.

(6) Complete absence of craters or holes at the base.

Figs. 32—36 show the progressive growth of the echoes on the PPI scope of a Nor'-wester type thunderstorm observed at Dum Dum on 27 April 1955. In Fig. 32 at 1400 IST may be seen the first appearance of a few cells of small diameter. An hour later, the number of cells had become large with a tendency to form a line (Fig. 33). By 1600 IST (Fig. 34), these have developed into a full fledged Nor'wester, very similar in nature to frontal or squall line thunderstorm moving towards the station. At 1655 hrs the cell towards due west had become intense and is about to come over the station (Fig. 35). Fig. 36 shows the situation when the Nor'wester has come over the station with accompanying squall. Fig. 37 shows the column type of echoes observed at New Delhi. It will be seen that they are cylindrical in shape and show little variation in intensity with height.

Figs. 38—43 show the progressive growth of the radar echoes on the RHI observed at Dum Dum on 30 May 1958 associated with another Nor'wester. The column type characteristic of the echoes, their sudden growth in the course of 10 minutes from 13 to 18 km and the decrease in intensity and vertical thickness is quite evident from Figs. 38-40 and 41-43 respectively.

Another example of the echoes observed on REI of a similar situation at Dum Dum on 22 May 1959 is reproduced in Figs. 44-45 in which the change from towering cumulus to cumulonimbus is brought out. It will be seen that in all these pictures there is a complete absence of the melting band.

Figs. 46—49 show the radar photographs of the REI type at Poona when a bright band appears sometimes in the dissipation stages of a thunderstorm. It will be seen that the cellular structure observed in the case of bright band associated with air mass type of thunderstorm is completely absent here.

On the basis of the above, the three types of thunderstorms can be distinguished from one another in the following way—

(*a*) *Cold front thunderstorms*—These will be characterised by

(1) A pressure rise and temperature fall of the persistent type (Fig. 1).

(2) Precipitation echoes, which will be along a line on PPI scope.

(3) Precipitation echoes of the column type on the RHI.

(*b*) *Air mass type thunderstorms*—These are characterised by

(1) Pressure and temperature variation of the non-persistent type (Fig. 2).

(2) Precipitation echoes which will be of scattered type on a PPI and some of them will show craters.

(3) Evidence of formation of echo from near the freezing level.

(4) Precipitation echoes showing multiple cellular structures descending from aloft downward on the RHI.

(c) *Nor'wester type thunderstorms*—These are characterised by

(1) Pressure and temperature variations of non-persistent type.

(2) Precipitation echoes of scattered type with complete absence of craters on the PPI.

(3) Absence of evidence of formation from aloft.

(4) Precipitation echoes showing single cells ascending from lower levels aloft on RHI.

(5) Column type of echoes on the RHI.

(6) Characteristics similar to those mentioned in (2) above under cold front when the downdraft gives rise to thunderstorm along a line of discontinuity.

REFERENCES

Desai, B. N. and Mull, S. 1938 *Beitr. Geophys.*, **53**, pp. 285-304.

Mull, S. and Rao, Y. P. 1949 *Indian J. Phys.*, **22**, 12, pp. 531-538.

1950(a) *Indian J. Met. Geophys.*, **1**, 2, pp. 116-136.

1950(b) *Ibid.*, **1**, 4, pp. 291-297.

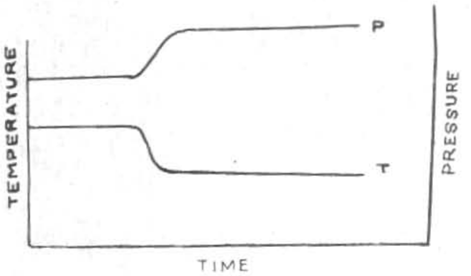


Fig. 1

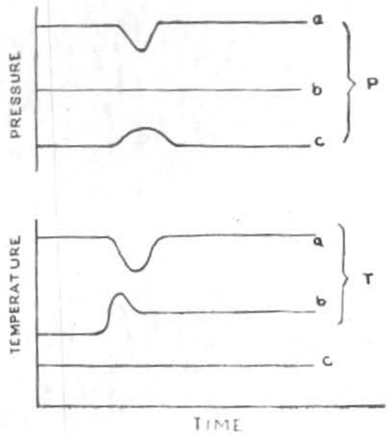
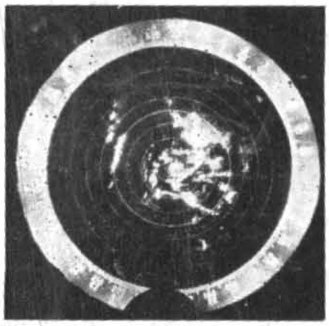


Fig. 2

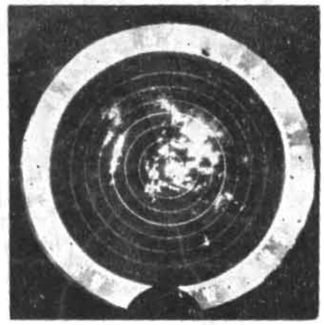
1344 IST 200 mi, 1°

Fig. 3



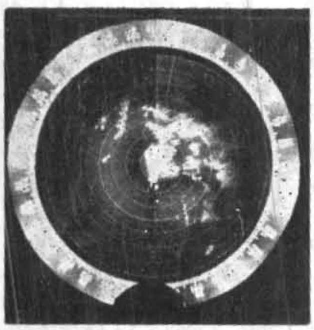
1442 IST 200 mi, 1°

Fig. 4



1458 IST 200 mi, 1°

Fig. 5

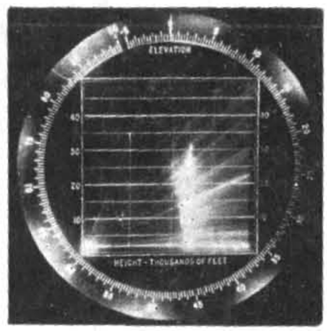


1651 IST 200 mi, 1° 20′

Fig. 6

1859 IST 200 mi, 1°

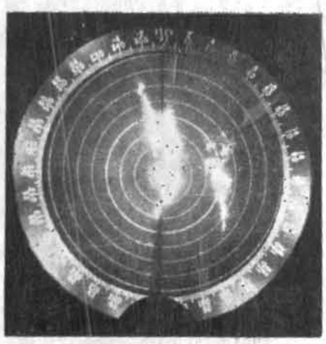
Fig. 7



1902 IST 100 mi. 309°

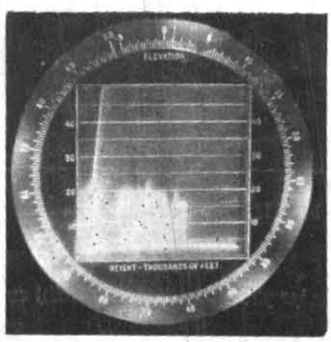
Fig. 8

Figs. 3-8. Radar photographs at New Delhi on 28 January 1959



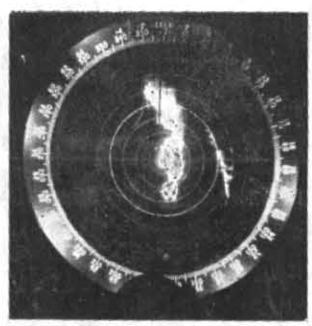
0032 IST 200 mi, 1°

Fig. 9



0035 IST 75 mi, 165°

Fig. 10



0115 IST 200 mi, 1°

Fig. 11

Figs, 9-11. Radar photographs at New Delhi on 29 January 1959

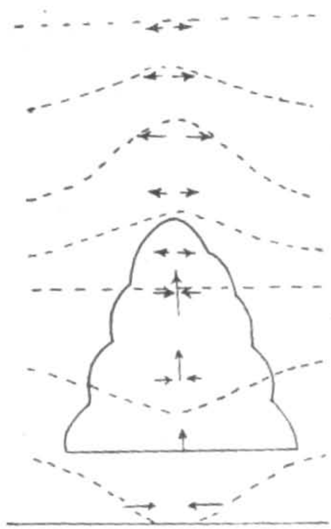


Fig. 12

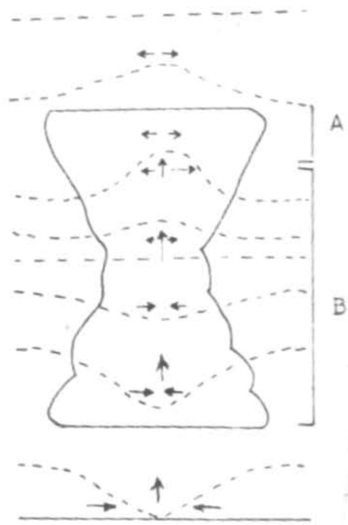


Fig. 13

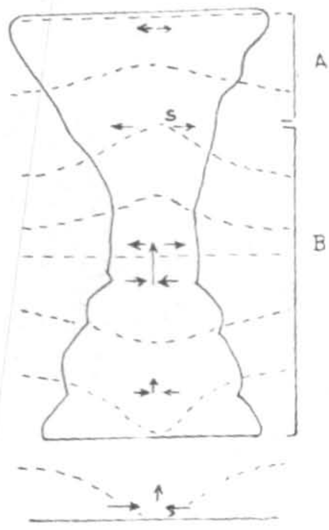
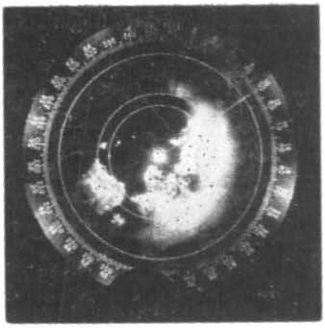


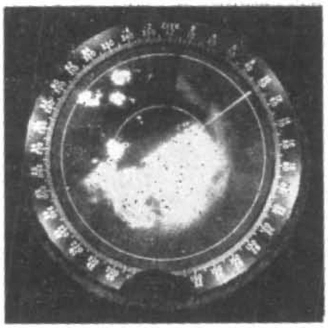
Fig. 14

A—Cloud air denser than environment
B—Cloud air less dense than environment



1308 IST 50 mi, 10°

Fig. 15



1405 IST 50 mi, 10°

Fig. 16

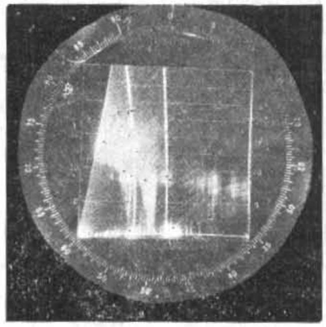
1406IST 50 mi, 5°

Fig. 17

Fig. 15-17. Radar photographs at New Delhi on 7 July 1958

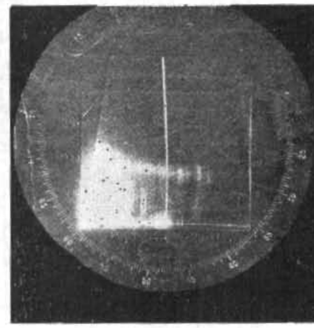
1435 IST 50 mi, 5°

Fig. 18



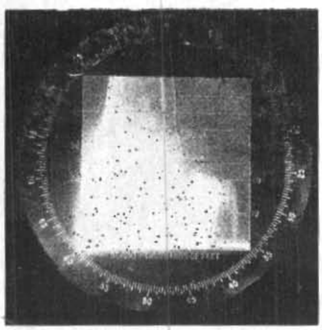
1252 IST 50 mi, 080°

Fig. 19



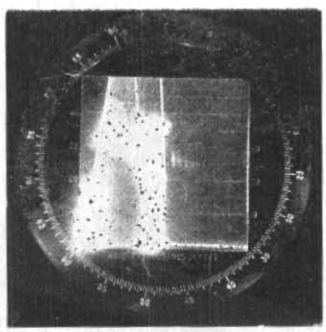
1359 IST 50 mi, 080°

Fig. 20



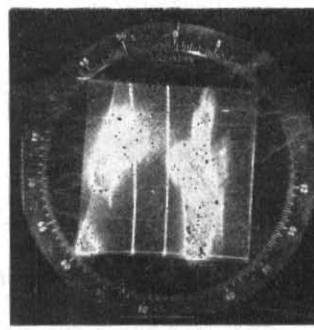
1400 IST 50 mi, 080°

Fig. 21



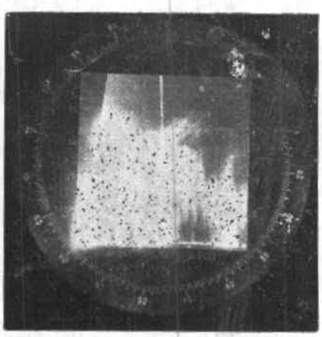
1402 IST 50 mi, 274°

Fig. 22



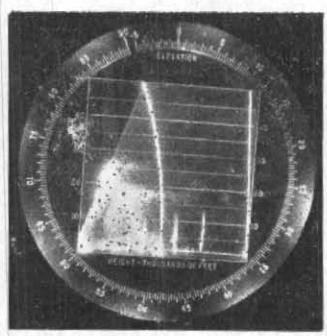
1253 IST 50 mi, 240°

Fig. 23



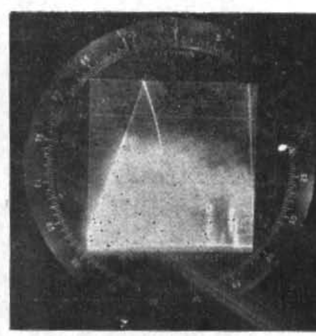
1359 IST 50 mi, 230°

Fig. 24



1912 IST 25 mi, 056°

Fig. 25



1913 IST 25 mi, 056°

Fig. 26

Figs. 18-26. Radar photographs at New Delhi on 7 July 1958

←-Circular holes

0015 IST 5 miles

Fig. 27. New Delhi, 15 January 1953

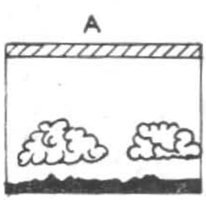


Fig. 28

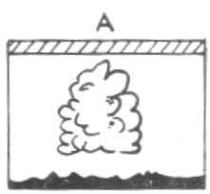


Fig. 29

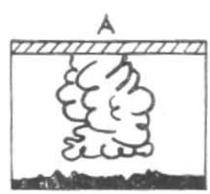
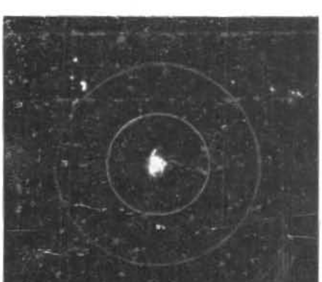


Fig. 30

Fig. 31

A— Boundary layers

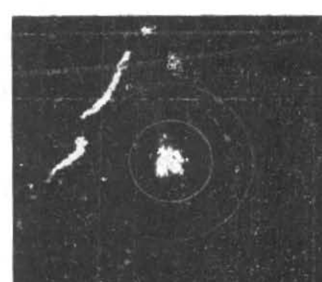


1400 IST 0°/50 mi

Fig. 32

1450 IST 0°/50 mi

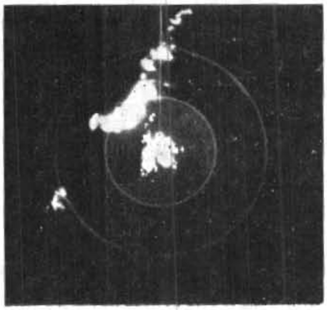
Fig. 33



1600 IST 0°/20 mi

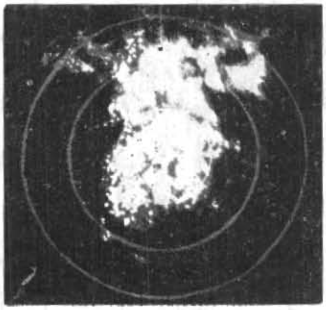
Fig. 34

Figs. 32-34. Passage of a Nor'wester over Dum Dum on 27 April 1955



1655 IST 0°/20 mi

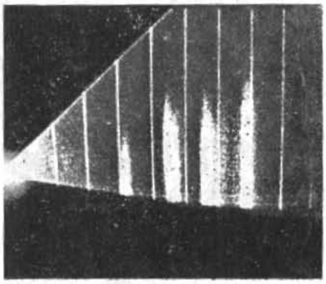
Fig. 35



1734 IST 0°/5 mi

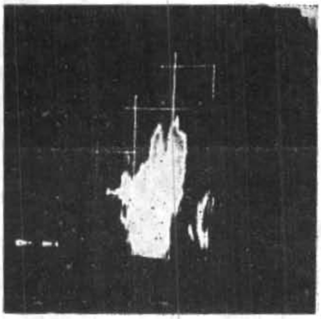
Fig. 36

Figs. 35-36. Passage of a Nor' wester over Dum Dum on 27-4-1955



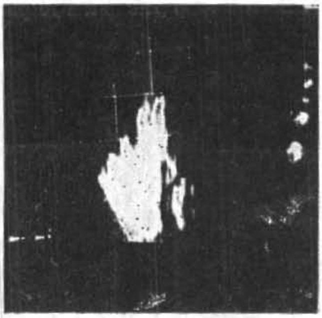
1657 IST '50 mi, 10°

Fig. 37. New Delhi, 12-3-1956



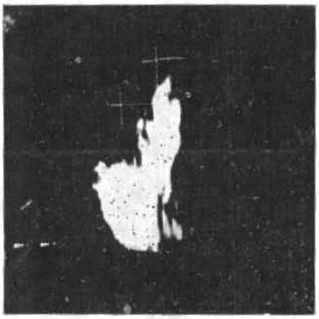
1515 IST 50 km, 176°

Fig. 38



1520 IST 50 km, 276°

Fig. 39

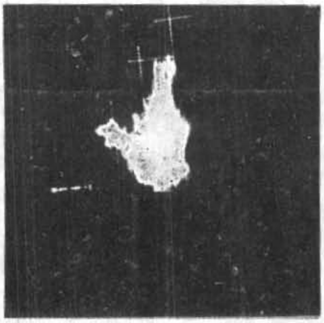


1525 IST 50 km, 276°

Fig. 40

1536 IST 50 km, 270°

Fig. 41



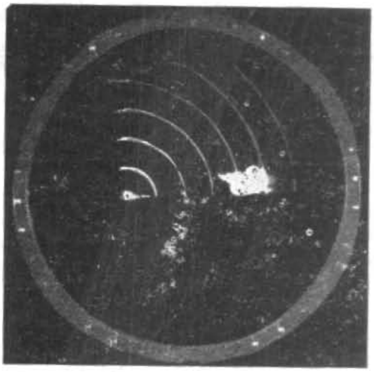
1539 IST 50 km, 270°

Fig. 42

1541 IST 50 km, 270°

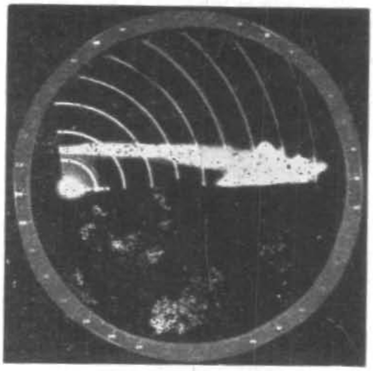
Fig. 43

Figs. 38-43. Radar photographs at Dum Dum on 30 May 1958
Markers are at 10 km



1719 IST 010°

Fig. 44



1810 IST 009°

Fig. 45

Radar photographs of Dum Dum on 22 May 1959

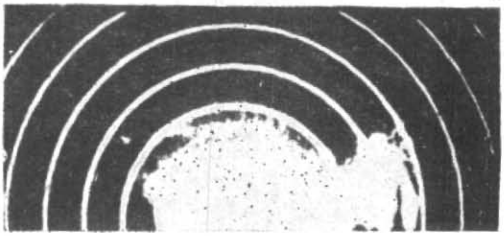
Range markers are at 20 and 10 km respectively

W E

1450 IST 5 mi

Fig. 46

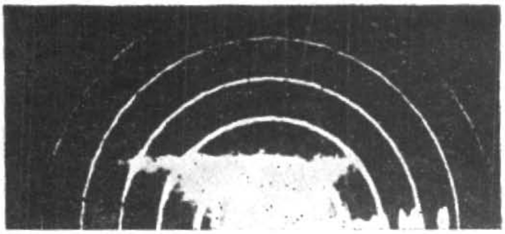
W E



1455 IST 5 mi

Fig. 47

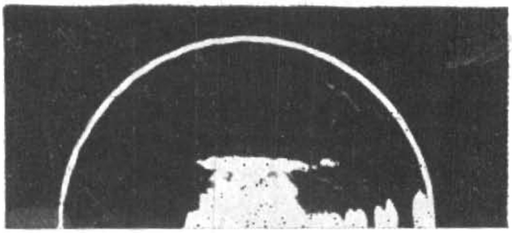
W E



1517 IST 5 mi

Fig. 48

W E



1750 IST 5 mi

Fig. 49

Figs. 46-49. Bright band in thunderstorm at Poona on 7 September 1953

Scanning horizon to horizon west to east