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Classification and interpretation of Radar Weather Echoes in India

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ABSTRACT. In the paper, a classification of various types of radar-weather echoes in tropics has been attempted. The different types of precipitation echoes have been categorised under the heads—(1) Feature type, (2) Synoptic type and (3) Seasonal type. In order to be able to distinguish the real precipitation echoes from those due to super-refraction etc, the various types of non-precipitation echoes have been described in the second part of the paper. Classification of radar echoes has been attempted with a view to provide guidance material to meteorologists in India in the identification and interpretation of radar-weather echoes. It is based on the data so far collected in India and is likely to be changed or modified as more experience is gained.

Introduction

The adoption of radar in meteorology has provided a new aid to the forecaster in his day-to-day work. With the help of radar, a meteorologist can have a fairly accurate three-dimensional picture of the zones of precipitation and turbulence round the radar station at any instant of time. It has also vast potentialities in the domain of physical-meteorological research and other allied fields.

However the proper understanding, assessment and interpretation of radar weather echoes are not governed entirely by universal thumb rules but have special regional and seasonal aspects. The professional radar-meteorologist in the tropics is often faced with the problem of identifying and interpreting what he sees on the radarscope and finds himself in a dilemma due to non-availability of sufficient guidance material. It is to make up this deficiency that an attempt has been made here to classify and arrange a large volume of data available in this country from the observations made during the last few years. A preliminary attempt at this type of classification was made by the senior author some time back (Mathur 1960) and, with further experience gained since then, it has now been possible to give a more elaborate account of the subject. It is hoped that the present paper will serve as a useful guide for the assessment and interpretation of radar weather echoes in a tropical region like India.

The paper is divided into two parts. Part A deals with Precipitation Echoes and Part B deals with the Non-precipitation Echoes.

PART A — PRECIPITATION ECHOES

To simplify the interpretation of precipitation echoes, a classification of them into three main groups and their sub-groups has been attempted in the following paragraphs. The three main groups may be taken as —

(*a*) Feature type, (*b*) Synoptic type, and (*c*) Seasonal type.

These types and their sub-classifications are discussed below.

(*a*) *Feature type*

As a first step in the interpretation of precipitation echoes, it may be helpful to classify them with respect to their characteristic features, more or less depending upon their shape and size which give them distinctive appearance on various radarscopes. These echoes may broadly be divided into the following seven sub-groups —

(1) Convective, (2) Stratiform, (3) Bright Band, (4) Shear, (5) Dry Holes, (6) Protuberances and (7) Spiral Bands,

Fig. 1(a). Convective cells on PPI

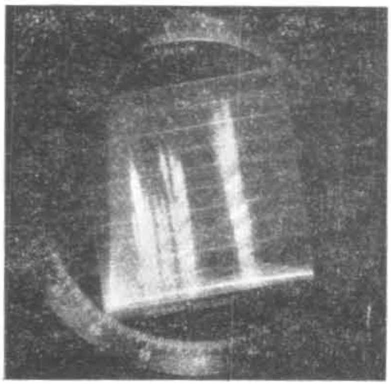

Fig. 1(b). Convective cells on RHI

1. Convective type

In the classification of echoes, the first thing is to decide whether it is of convective or stratiform type. There are, of course, borderline cases in which it might become difficult to reach a decision. Further there are occasions when echoes are simultaneously convective at one level and stratiform at another level in the atmosphere. However, for the purpose of classification, it is preferable to give clear-cut examples which illustrate the difference between the two and serve to provide material for further identification and classification.

The convective type of echoes can be seen in the photographs in Figs 1 (a) and 1 (b) and have the characteristics mentioned below.

(*i*) On the PPI-scope, they are circular or oval shaped echoes of relatively smaller sizes with clear-cut and sharply-defined edges as seen in Fig. 1(a),

(*ii*) Each echo may be a single convective cell or a group of closely-packed cells,

(*iii*) On the RHI-scope, convective type of echoes are in the form of tall narrow columns as seen in Fig. 1 (b),

(*iv*) They are quite bright in intensity,

(*v*) Due to their great vertical extent and high intensity, they can be detected even on long ranges,

(*vi*) They do not exhibit any bright band except some times in the decay-stage of the convective cell,

(*vii*) These convective echoes show iso-echo contours,

(*viii*) They are associated with convective phenomena,

(*ix*) High water content and updrafts are responsible for severe turbulence within such echoes. Therefore, the brighter portions of a convective echo will denote regions of severe turbulence,

(*x*) Extraordinary brightness in a convective cell is indicative of the presence of hail,

(*xi*) Blurring of the edges of a convective type echo is the first indication of the beginning of decay of the cell, and

(*xii*) On reduction of receiver gain, the reduction in the size of a convective echo is comparatively less than that of a stratiform echo.

2. Stratiform type

Typical examples of stratiform type of echoes can be seen in Figs. 2(a) and 2(b). Some of their characteristics are given below.

(*i*) On PPI-scope, they are rather large in size and appear more as echo "patches" rather than echo "cells". They have diffuse and ill-defined edges,

(*ii*) On RHI-scope, the height to width ratio is small for stratiform echoes. The echoes do not show large vertical development,

(*iii*) They are more or less of uniform intensity and are much less bright than convective type of echoes,

(*iv*) Due to their limited vertical extent and low intensity, they cannot be detected at long ranges,

(*v*) Due to the weak nature of the stratiform echo, even a small amount of intervening precipitation is sufficient to mask the echo,

Fig. 2(a). Stratiform echo on PPI-scope

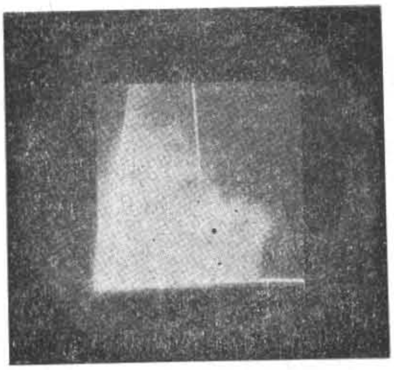

Fig. 2(b). Stratiform echo on RHI-scope

(*vi*) They very often exhibit bright band,

(*vii*) Generally they do not exhibit any iso-echo contours,

(*viii*) They are associated with stable type of weather phenomena,

(*ix*) There is almost no turbulence associated with a really stratiform echo,

(*x*) For the same reduction of receiver gain, the reduction in the size of stratiform echo is much larger than the reduction in size of a convective echo, and

(*xi*) An echo which begins as a convective cell may, in the final stages of its decay, completely degenerate into a stratiform type of echo.

3. Bright Band

Bright band is associated with stratiform type of echoes and can be seen on RHI-scope on reduction of receiver gain. It is found to occur in the vicinity of the 0°C isotherm. A typical bright band within a stratiform echo can be seen in Fig. 3.

A well-defined bright band can be seen only under stable conditions of the atmosphere when the up-currents are either uniform or weak. It is, therefore, a good indicator of the presence of instability or otherwise in the atmosphere. A knowledge of the altitude of 0°C isotherm is of great use to the aviator specially in avoiding the troubles due to icing. The presence of a bright band gives the altitude of 0°C isotherm with a reasonable accuracy. This method of estimating the altitude of 0°C isotherm can be useful in regions of sparse radiosonde network and over ocean areas.

Thus a knowledge of the presence of a bright band in a given echo is useful for two reasons. Firstly it helps to decide that the echo is really purely stratiform and has almost no turbulence associated with it; secondly it gives the altitude of the 0°C isotherm. It is, therefore, very important that all radars, having the facility of RHI-scope, should be utilised to search for the existence of bright band in every echo pattern which appears to be of the stratiform type.

4. Wind Shear

When precipitation shows showery characteristics, the cells may be seen on RHI-scope as separate columns of falling rain or snow. These columns often slant out of the vertical due to wind shear, as may be seen in Fig. 4.

To understand how the shower columns get bent, we may consider that the precipitation originates at a higher level in the atmosphere. As the snowflakes or raindrops fall to a lower level with different wind speed and direction, the drops are deflected laterally by the shearing wind. Because the wind differences between the two levels may be large compared to fall velocities, the slope of precipitation columns may be very steep, particularly with snow where the fall velocities may be only a few cms per second.

To observe the shear effect clearly, the radar must be pointed such that the antenna scans in the same vertical plane as that of the wind shear. In such cases, it may even be possible to estimate the distribution of winds aloft from the RHI pattern. However care must be exercised in interpreting the RHI pattern when the radar antenna is not pointing in the plane of the wind shear. When looking cross-wind, the radar beam intercepts only

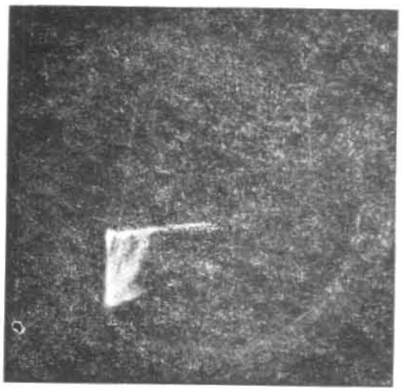

Fig. 3. Bright band in stratiform echo

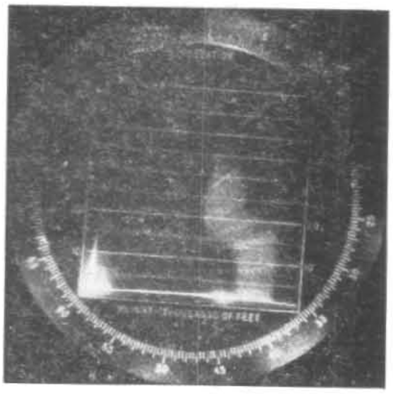

Fig. 4. Presence of wind shear as seen on RHI-scope

that portion of a sloping shower which falls along the particular azimuth being scanned, giving the appearance of the component of the shower aloft in that particular azimuth.

From a study of the relation of wind shear and cloud shear, it is found that, in general, the radar cloud shear in mature thunderstorms and showers is about 50 to 75 per cent of the wind shear. According to Battan (1959), this can perhaps be explained by considering the transport of horizontal momentum by the thunderstorm drafts.

It is also found that when wind shear exists, new radar cloud turrets develop on the side of the cloud upwind of the shear vector. On the other hand, new cells are found to be most frequent on the side of the cloud in the direction towards which the cloud is moving.

5. Dry Holes

Sometimes, a very curious phenomenon is observed when small areas, apparently with no precipitation, are found embedded in very large and extensive areas of heavy precipitation. These have been called "Dry Holes" and should not be confused with the black areas appearing in a convective echo on the application of iso-echo contouring device available in certain weather radars, as for example in Bendix radar WTR-1.

The dry holes are thought to be areas of no precipitation because the radar beam is (as can be seen in Fig. 5) strong enough to penetrate many more miles beyond these dry holes and give detectable echo. The important question is: why should there be few small dry areas of the order of 5 square miles or even less in a large, extensive and heavily precipitating area of say 2000 square miles or more? A suitable physical explanation for this phenomenon is not yet available but in U.S.A., these are found to be associated with tornadoes and sometimes with hail. In India, we have so far not found them to be associated with tornadoes. There is also no evidence to show that these are associated with hail. The only conclusive point about their occurrence in India is that these are associated with severe storms in which precipitation rate is high and surface winds are strong. The occurrence of "dry holes" in extensive precipitation echoes can be taken as a positive evidence of the fact that the storm is going to develop into a severe one. A definite confirmation of this observation will come in course of time when more data become available.

6. Protuberances or Appendages

The radar weather echoes from which such hooks extend are generally intense and the hooks themselves show high intensity as well. Typical pictures may be seen in Figs. 6 (a) and 6 (b). The hooks usually (but not necessarily) appear on the upwind and right hand side of an echo, *i.e.*, SW portion of an echo moving east. Such hooks may be masked by weather echoes at high gain. Therefore the echo under observation should be surveyed periodically at low gain. Further, such hooks may appear at higher antenna elevations but not at zero degree.

These protuberances, hooks or appendages jutting out of very intense convective echoes should always be taken to be indicative of hail and other severe weather phenomena. The occurrence of an appendage is most significant when detected at lower elevation. The closer the elevation angle is to 0°, the more representative will the radar observation be of the surface conditions, such as hail on ground. This criterion, when used alone, must however be used with great caution.

Fig. 5. Dry Holes as seen on PPI-scope

Fig. 6(a). Hook as seen on NMD-451A radar

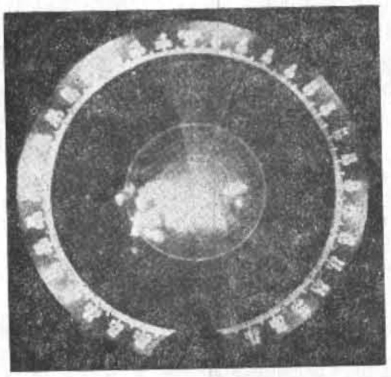

Fig. 6(b). Hook as seen on AN/CPS-9 radar

Fig. 7. Spiral bands in Bay Cyclone

However, when an echo possesses a clearly defined '6' shaped appendage, with dimensions of 5 to 10 miles, and satisfies several other criteria for severity, it is very likely to be a tornado aloft, if not on the ground.

7. Spiral Bands

Sometimes echoes are observed in the form of spiral bands. It has been found that in such cases, some form of logarithmic spiral appears to conform to the echo pattern. A typical example of such an echo taken over the Bay of Bengal near Calcutta is shown in Fig. 7.

The spiral echo pattern is quite obvious and prominent in most of the revolving storms in ocean areas and can be seen for long periods of time. In other revolving storms, the echo pattern is not so distinct, specially after the storm has had an overland trajectory.

(*b*) *Synoptic classification*

We will now pass on to the echo classification associated with a few broad synoptic weather situations which may provide some helpful information on the interpretation of weather associated with them so as to prove to be of some use to the forecaster.

Weather patterns are so complex that it is customary to use greatly simplified schematic presentations in describing them. Until the advent of radar, the sparsity of reporting stations precluded a detailed examination of precipitation patterns. Radar clearly shows the detailed structures which are present in each separate situation within the general pattern of precipitation. Just as one would say, "No two weather maps are exactly alike"; so also one could say, "No two radar presentations are exactly alike". Every pattern has its own characteristics. These will be indicated in the following paragraphs. The forecaster will soon realise and appreciate that the radar will give him a much more detailed picture of the "shaded green area" on his synoptic map.

It is emphasised that it is impossible to determine the synoptic situation from the radar presentation alone. The radar will only be an aid to the forecaster whose main tool is his synoptic chart.

In the following paragraphs, it is intended to give the general characteristics of radar echo patterns associated with certain weather phenomena and broad weather situations. A detailed analysis of any particular pattern will always reveal some special features; but in most of the well known synoptic patterns, there are certain general features which are characteristics of the situation and are commonly observed. These typical patterns are described in this section together with some typical radar photographs.

(1) Thunderstorm echoes

Radar weather echoes from thunderstorms have generally clearly-defined edges and well-developed vertical structures. The tops of the echoes, as seen on RHI-scope, may or may not show the anvil shape. Thunderstorm cells often have a tendency to conglomerate into a band or line irrespective of the fact whether they occur during a frontal situation or during purely air-mass activity.

A phenomenon which may only rarely be observed during thunderstorm activity is a radar echo from lightning. This is hard to pick out on most of the radars (specially on radars with narrow beam and short pulse length — such as those at present in use in the India Meteorological Department) but by employing careful search procedures, lightning echo may sometimes be seen at reduced receiver gain. The lightning can be momentarily seen on R-scope comparatively easily as an intensification of the echo at a range corresponding to the distance of the discharge. This intensification is caused by the increased reflectivity of the ionised air in the vicinity of the electrical discharge and not by propagation of electromagnetic radiation from the source of lightning as in case of sferics.

If a lightning echo is observed, it is a positive proof of the echo being a thunderstorm cell. The reverse is, however, not true as it is very easy to miss the lightning stroke — specially with a scanning antenna — the problem being of sampling the proper volume at the appropriate time.

Further classification of Thunderstorm echoes — A preliminary study of synoptic weather situation in relation to radar echo patterns in India on days of thunderstorm activity, shows that they can be conveniently classified under the following three types—

(*i*) *Thunderstorms along a line* : These are sometimes associated with cold fronts of some western disturbances over north India in winter.

(*ii*) *Air-mass thunderstorms* : These occur in the same airmass and may also be called Heat thunderstorms.

(*iii*) *Thunderstorms associated with upper air discontinuity* : These occur more or less simultaneously over a large area and are associated with a surface of discontinuity at some higher level. These thunderstorms are characterised by a very rapid growth, almost with explosive violence, of a towering cumulus when its head reaches the surface of separation. Nor'westers of Bengal and most of the *Andhis* of northwest India fall in this category.

The echo characteristics of these three types are described below —

(*i*) *Thunderstorms along a line* — Echoes from the upper portions of cumulonimbus clouds along a long band appear on PPI-scope as long, rarely continuous, narrow bands due to the finite beamwidth and consequent poor discrimination by the radar set. These features can be seen in the radar photograph reproduced in Fig. 8.

As the line of thunderstorms comes nearer, the band of echoes begins to appear as composed of a large number of cells, often with very little separation, which break up and form again and change constantly in shape and size as they pass across the scope. Although the actual cloud structure along the line may be almost solid with narrow bands, the band of echoes often appear discontinuous on PPI-scope as the portion of associated cloud contains drops of too small a size and poor concentration to give detectable echo.

When the line of echoes is very near the station, the radar echoes again lose their cellular structure which can be easily seen by reducing the receiver gain in order to get rid of the weaker echoes caused by drops of smaller sizes. The individual cells on RHI-scope show typical cellular structure representing cores of strong vertical movement associated with cumulus or cumulonimbus cloud at the leading edge of the band.

This trend continues until the line passes over the station when the echoes from the more distant storm cells become weak because of rain attenuation and the precipitation appears to be almost evenly distributed around the radar station over a distance of many miles.

After the passage of the storm over the station, the above sequence of events are reversed until the line of thunderstorm becomes diffused, weak or goes beyond the detectable range of the radar.

The apparent length of the line or front shows an increase (as it approaches the station) due to decrease in rain attenuatic except when the

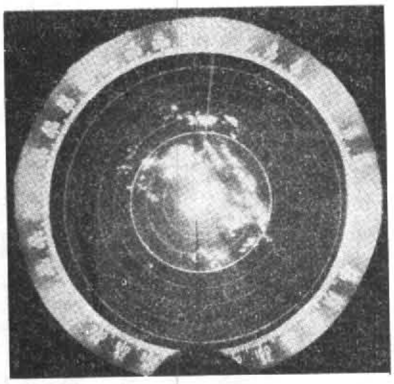

Fig. 8. Thunderstorms along a line

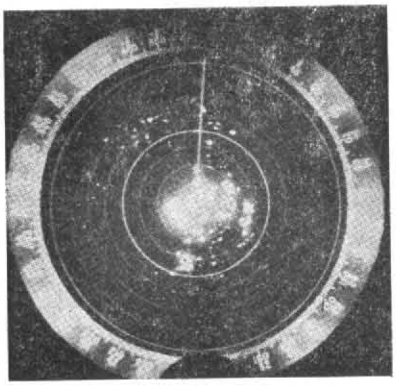

Fig. 9. Air-mass thunderstorms

disturbance is over the station itself and causes considerable absorption of radar energy due to heavy local rain thus masking the echoes from the outer portions of the front.

The width of the echoes along the line varies greatly with the distances as well as activity. The width increases with increased activity and as the front approaches the station.

Sometimes the thunderstorms associated with cold front are preceded by another prefrontal squall line type of thunderstorm, of comparatively weak activity, parallel to the main front. This prefrontal activity may be observed almost 50 to 60 miles ahead of the main front.

(*ii*) *Air-mass thunderstorms* — The radar weather patterns from air-mass thunderstorms are similar to the echoes shown in Fig. 9. The radar echoes from air-mass thunderstorms can be recognised by the following characteristics —

They are scattered and oval-shaped echoes with fairly clear-cut edges like those described earlier under convective type of echoes. They occur over a large area, growing and intensifying with time, as cumulus cells develop into towering cumulii.

On RHI-scope, they show large vertical development, roughly cylindrical in shape, consisting of a single column but at other times two or more columns may be seen particularly when they are associated with extensive cumulonimbus formations.

The echoes on RHI-scope show widening at the top thus indicating the spreading of vertical currents.

Echoes on RHI-scope sometimes show precipitation streaks from a higher level downwards.

(*iii*) *Thunderstorms associated with upper air discontinuity* — These are the thunderstorms associated with upper-air discontinuity. The radar weather patterns from this type of thunderstorms are characterised by the following features —

The echoes appear scattered on PPI-scope from cloud cells occurring over a large area, which grow and intensify with time, as the cumulus cells develop into towering cumulii.

On RHI-scope, the echoes are like columnar precipitation cells which show growth of precipitation from low levels upwards and show little change in the echo intensity with height. This may be very well seen in Figs. 10 (a) and 10 (b).

They are distinguished by the complete absence of bright band.

They show sudden and quick vertical development on RHI-scope due to rapid growth of the towering cumulus to cumulonimbus and with decrease of both intensity and vertical thickness due to their culmination into a thunderstorm. This is also very well seen in Figs. 10(a) and 10 (b).

The echoes appear similar to those associated with thunderstorms along a line when the downdraft gives rise to squalls along a line.

(2) Steady Rainfall

Steady precipitation and heavy nimbostratus clouds may be detected by a weather radar as a relatively featureless echo on the radarscope. During periods of widespread precipitation around the the observing station, the radar site will generally be at the geometric centre of the echo. An example is shown in Fig. 11. It should, however, be remembered that this presentation is not a true picture of the distribution of precipitation under such conditions. The precipitation is possibly too light to be detected by the radar beyond a certain range or is so widespread that it is lost below the radar horizon due to curvature of earth. The echo generally appears brightest in the centre of radarscope and the intensity decreases steadily with increasing range until it gradually merges with the background noise.

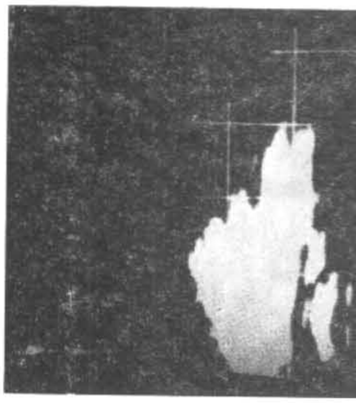

Fig. 10(a). RHI-scope presentation of a thunderstorm associated with upper air discontinuity

Fig. 10(b). Same thunderstorm few minutes later

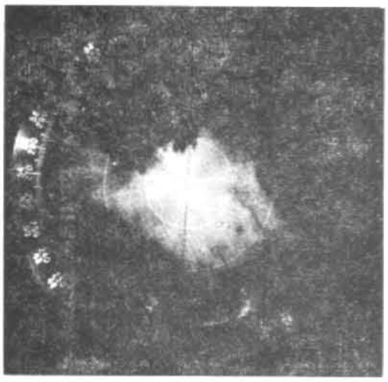

Fig. 11. Warm front rain

Fig. 12. Air-mass showers

The passage of a warm front, associated with a western disturbance, over the station also gives a typical sequence of radar echoes. A typical warm front echo will first appear on PPI-scope as a diffuse mass of echo at a distant range and gradually spread over larger area on the radarscope. The echo is often composed of faint and ill-defined bands. As the surface warm front approaches the station, the widespread precipitation fills the centre of PPI-scope with an echo of uniform intensity. With the further approach of the surface warm front, the precipitation generally changes somewhat in character breaking up into shower sometimes. The shower cells usually form into bands and move in the same direction as the front. It has often been observed that the precipitation associated with a warm front covers a larger area as compared to cold front precipitation.

3. Showers

Air-mass showers, during periods of relatively strong convective activity, appear as scattered echoes with sharply defined edges and well-developed vertical structures. Often these echoes merge into bands and move as squall lines. Air-mass showers tend to form, grow and dissipate rather quickly. It is necessary to keep a close check on PPI-scope pattern to watch the formation of new cells. The growth from a detectable echo cell to a well-developed one may take place within ten or fifteen minutes. Fig. 12 shows a typical example of echoes from air-mass showers. However, when convective activity is weak or the moisture supply is inadequate, the individual cells may be very small and may show poor vertical development. They sometimes arrange themselves in close groups and have a longer life-cycle than the more intense convective cells.

4. Squall Lines

A squall line pattern is similar in appearance to a cold front pattern except that the length to width ratio is larger for squall lines than that for cold front echoes. An example is shown in Fig. 13. Squall-line echoes are characterised by cellular bands oriented parallel and close to the surface position of the convergence zone. The movement of the bands generally approximates the movement of the squall line but sometimes the speed of the band is greater. In these cases, the bands apparently form in the rear of the convergence zone, move through and dissipate on the leading edge of the zone. The cells within the bands are constantly undergoing a process of formation and dissipation. They appear to form and intensify on their forward edge and dissipate on their trailing edge. The velocity of the individual cells is generally different from that of the band in which they are embedded.

5. Cyclones

An example of the typical echo pattern associated with cyclone has already been shown in Fig. 7. Echoes from these storms are usually distinctive in appearance but it must be remembered that attenuation, in the heavy precipitation associated with these storms, may modify considerably the precipitation pattern in some sectors. The first manifestation of such a storm may be the observation of echoes from squalls that are moving in a direction opposite to that usually prevailing in the area. As the storm develops, circulation of echoes about a centre becomes complete. The character of the echoes associated with tropical cyclones varies according to their position relative to the centre.

In the periphery of the storm, echoes are convective and cellular, sharp-edged and bright. These have large vertical extent and, on occasions, may be seen as far as 600 km from the storm centre. After these echoes, there is sometimes observed a relatively echo-free area about 80 km in extent followed by a large area of very bright echo. This echo, under reduced receiver gain, exhibits spiral-banded structure. These spiral bands are in the shape of equiangular spirals and follow the equation, $\log_e r = A + B\,\theta$, where A and B are constants. Then in the centre of storm is the 'eye' of the storm. This is again an almost echo-free area.

Recently, a cyclonic storm in the Arabian Sea could be photographed from the U.S. Research aircraft, DC-6, taking part in the International Indian Ocean Expedition. The radar photographs of this storm were taken on 24 May 1963. Both RHI and PPI pictures can be seen in Fig. 14 (a) and 14(b). In the RHI-scope picture, the eye of the cyclone can be clearly seen with eastern and western walls of heavy precipitation with a clear region in the centre corresponding to the eye of the cyclone. These photographs have been reproduced here through the kind courtesy of Prof. C. S. Ramage.

6. Hailstorms

Hail is invariably associated with violent convection and the radar echoes which have been positively identified with hail have shown the sharp-edged, high intensity echoes characteristic of convective type. In fact in most of the cases, the extra-brightness of the echo is a good criterion for the presence of hail. An unusually bright convective echo should always be suspected to be with hail formation.

In many cases, however, hail has been found to be associated with protuberances or hooks from the edges of very bright convective type echoes. An example of hook formation which was definitely associated with very large sized hail has already been shown in Fig. 6(b). But it should be clearly borne in mind, that the shape (of the echo) alone can do no more than indicate the possibility of the presence of hail and much more information can be gathered from considerations of intensity of the echo, specially in case of hail of damaging size. Local experience will show that for a particular radar set, there is a threshold value of echo intensity at a specified range above which there would be a strong probability that hail of damaging size may be present.

(c) *Seasonal classification*

In this section, an effort has been made to describe the types of radar weather echoes expected in various seasons in different parts of India. Obviously such an introduction will raise the hope of finding here various radar weather pictures in different seasons in various regions of the country. But what has been attempted here is the description of the peculiarities of radar weather echoes of important regional storms. The radar echo characteristics of almost all the available types have already been described in the preceding paragraphs.

1. Winter Season (December to February)

In this season, the main weather is due to western disturbances in the northern parts of the country and thunderstorms associated with northeast monsoon in the southern parts (Madras State and adjoining areas during October to December). The western disturbances passing eastwards through the north of the country, sometimes induce secondary systems over central parts of India. These secondary systems also have a tendency to move eastwards.

The radar echoes associated with the passage of western disturbances or their induced secondaries are mostly in the form of convective type of cellular echoes, aligned in a line, and move to east or northeast. A typical radar picture of a western disturbance is given in Fig. 15. The associated heights of tops are of the order of 30,000 to 40,000 feet. The

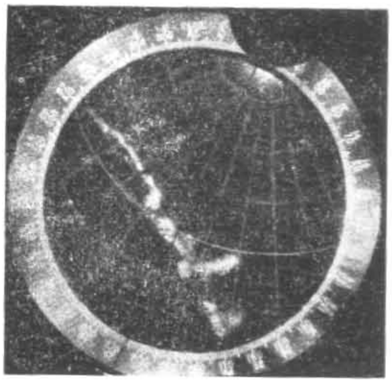

Fig. 13. Squall line

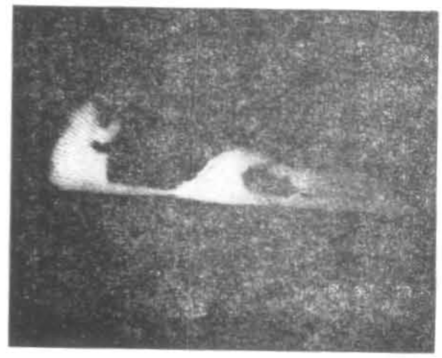

Fig. 14(a). RHI picture of the Arabian Sea cyclone of 24 May 1963

Fig. 14(b). PPI picture of the Arabian Sea cyclone of 24 May 1963

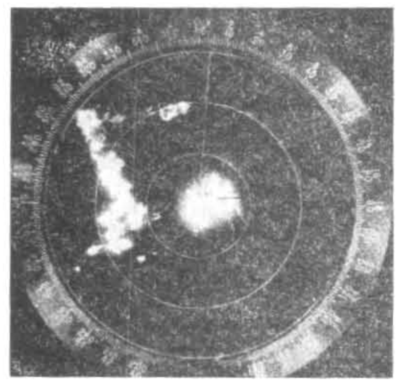

Fig. 15. Western disturbance

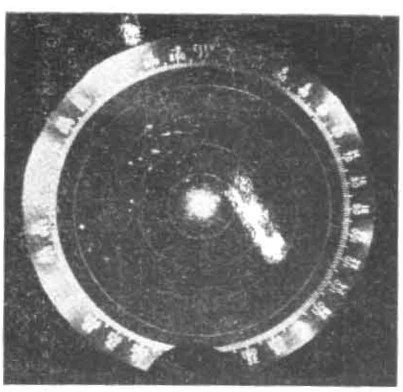

Fig. 16(a). PPI picture of duststorm

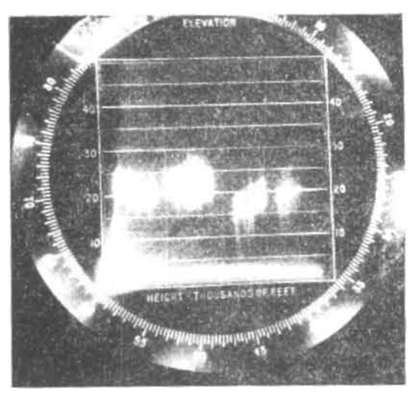

Fig. 16(b). RHI picture of duststorm

Figs. 14(a) and 14(b) — Photographs reproduced through kind courtesy of Prof. C. S. Ramage stratiform type of rain associated with western disturbances is generally too weak and confined to low altitudes and is not able to give a detectable echo except in the immediate vicinity of the radar station. There is a tendency for super-refraction to occur after the rain if winds are calm or sufficiently weak.

The thunderstorms that occur in the southern parts of the country in this season exhibit all the characteristics of convective type of echoes and sometimes align themselves in squall line formations.

The only other feature of this season is the occurrence of fog, specially in north India, but fog cannot be detected by the radars of the wave length used in the India Meteorological Department.

2. Summer Season (March to May)

The special weather phenomena occurring in this season are the following —

(*i*) Summer thunderstorms (duststorms) of northwest India,

(*ii*) *Andhis* of northwest India,

(*iii*) Nor'westers of east India,

(*iv*) Cyclonic storms in the Bay of Bengal and the Arabian Sea.

(*i*) *Summer thunderstorms* (*duststorms*) *of northwest India* — As the summer season in north India advances, the lower atmosphere gets drier and the amount of rainfall reaching the ground after a thunderstorm becomes less and less because of excessive dryness in the lower levels. In fact, the falling rain sometimes completely evaporates before it reaches the ground. The horizontal extent of the thunderstorm cells also becomes small and the associated drafts raise huge amounts of loose dust which is available in large quantity on the dry ground below.

Such duststorms give characteristic presentation on radarscopes as shown in Figs. 16(a) and 16(b). Since they are convective phenomena due to insolation, they appear on PPI-scope as small, oval, randomly distributed, convective echoes of the air-mass or heat type. The pattern on RHI-scope is very characteristic. The echoes on RHI-scope occur as upper truncated portions of cumulonimbus cells, as if hanging in mid-air, with rain streaks starting downwards but not reaching the ground as may be seen in Fig. 16(b). The radar characteristics of these storms have been discussed in detail by Mitra and Kulshrestha (1961). It should be remembered that as these echoes do not extend upto ground, the radar antenna has to be tilted upwards by 1° or 2° when searching at close ranges.

(*ii*) *Andhis of northwest India* — These are not the ordinary duststorms which are associated with almost all cumulonimbus developments in this season. *Andhis* are characterised by their great violence, huge blinding columns of dust, squally weather, lightning, sometimes associated with rainfall and at times hail.

The radar echoes first appear on PPI-scope like the air-mass thunderstorm echoes. Suddenly some of them are found to grow in intensity and on RHI-scope the tops can be seen rising fast. Within a matter of minutes, they align themselves in a line pattern and move giving rise to *Andhi*. The rest of the randomly distributed air-mass type echoes dissipate after sometime when convection due to insolation gets weakened.

(*iii*) *Nor'westers of east India* — The nor'westers of Bengal are the real aviation hazards. They are known as *Kal-Baisakhis* locally in eastern India which means the "Doom of Baisakh month". They are characterised by huge, black, ominous, rolling clouds associated with specially severe up and down drafts, very severe turbulence, lightning and excessive rainfall. They are known for their suddenness as is seen in Fig. 10.

The echo characteristics are exactly similar to those of *Andhis* because both are more or less similar in origin. The only difference is that whereas *Andhis* raise huge columns of dust, there is almost no dust associated with nor'westers. The resultant echo is very bright in their case. It is also thought that the heights of tops of nor'westers echoes are perhaps the highest observed anywhere any time.

(*iv*) *Cyclonic storms of the Bay of Bengal and the Arabian Sea* — There have not been many radar observations of cyclonic storms over Indian Seas, but the chief characteristics of their echoes are nevertheless well known and have been described earlier under synoptic classification. In this connection, Figs. 7, 14(a) and 14(b) may also be referred.

The exact location and further movement of the storm can be estimated only if the position of the "eye" can be determined precisely. When the eye is still beyond the range of the radar but when spiral bands are seen on radarscope, the position of the eye can be estimated by the geometry of the spiral bands. For this purpose, it is most useful to keep ready a few plastic overlays with different spiral curves drawn on them. When the spiral bands are seen on PPI-scope, the eye of the cyclone can be fixed with the aid of the curve which best fits these observed spiral bands.

It may be mentioned here that a 3-cm radar is not very suitable for cyclone observations because

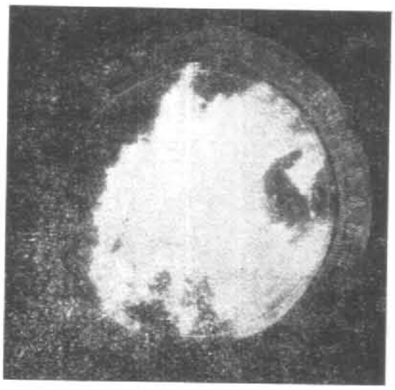

Fig. 17. Monsoon rain

of the attendant attenuation in the rain-belt. Wavelengths of the order of 5 cm or 10 cm are known to give better results. It is planned to instal, in the next five years, a few such powerful 10-cm radars along the coastline for the detection of cyclones in the Bay of Bengal and the Arabian Sea.

3. Southwest Monsoon Season (June to September)

This is the season in India when detectable rainfall occurs over large areas with the exception of a small rain shadow zone in Madras State. The major portion of the annual rainfall over the country occurs in this season. From the radar weather point of view, we can classify monsoon echoes into two types, *viz.*, those in coastal areas and those over inland areas.

In coastal areas, with the break of monsoon and only for a few days after that, there is thunderstorm activity. Thereafter it is all steady downpour with no lightning or thunder. It is, therefore, obvious that on the first few days of the break of monsoon in coastal areas, radar echoes are mainly convective or at the most a mixture of convective and stratiform types. Thereafter only stratiform type of echoes are observed. These, however, are of stronger intensity and extend to higher heights than the stratiform echoes observed in other seasons. Bright band is almost invariably seen.

Over inland areas, monsoon activity, when it is not continuous, is sometimes augmented by development of cumulonimbus clouds as a result of surface heating due to insolation. It is, therefore, seen that the echoes almost always start as convective types, becoming later a mixture of both convective and stratiform type and finally settling to purely stratiform type with high tops and intense brightness. In this final stage, bright band is displayed.

The heights of tops of echoes associated with cumulonimbus clouds are of the order of 40,000 to 50,000 ft and sometimes even higher. Monsoon echoes are always widespread covering large areas. A typical PPI-scope picture may be seen in Fig. 17.

4. Post-Monsoon Season (October and November)

The only significant weather in this season is the occurrence of cyclonic storms in the Bay of Bengal and the Arabian Sea. These exhibit the same radar characteristics as described above in connection with the cyclonic storms in summer season. Weather over the rest of the country is fair and settled.

PART B — NON-PRECIPITATION ECHOES

1. Importance of non-precipitation echoes

The meteorological radars were primarily intended for detection of precipitation elements but soon it was found that these radars were recording many echoes which were definitely not associated with any kind of precipitation. In recent years, a large amount of data has been collected from echoes observed from such regions of clear air. Because of the absence of visual targets, these clear-air echoes have come to be known as angels — a popular name given to the whole genera of non-precipitation echoes.

The study of these non-precipitation echoes is equally important: not only from the point of view of scientific study because they give us further insight into the structure and manner of working

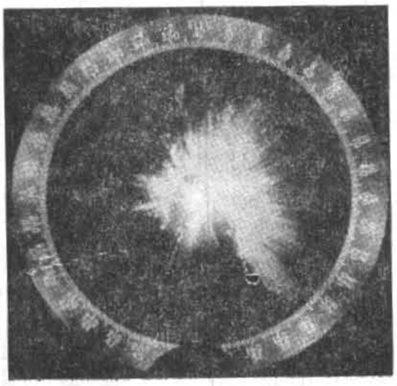

Fig. 18(a)

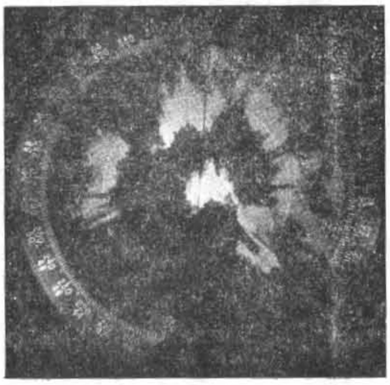

Fig. 18(b)

Normal super-refraction

of the lower atmosphere, but also from a practical point of view as these have to be distinguished from the real precipitation and other storm echoes so as to avoid confusion and unwanted weather warning. In addition, some of these non-precipitation echoes do show promise of becoming useful tools for short-range forecasting.

2. Normal Super-refraction

Super-refraction or anomalous propagation or guided propagation or duct propagation of radar beams is a well known and fairly well explained phenomenon. It is generally confined to a height of about 1000 ft or so above ground and is produced due to air layers in which the index of refraction decreases rapidly with height. Such variations of the index of refraction give to the path of the radar beam a curvature equal to or greater than that of the earth. A radar beam projected horizontally or nearly so may under these conditions be bent into a path which follows the surface of the earth or may even return to the earth. The radar beam in such a case behaves as if it were trapped in a duct. These ducts may be ground-based or elevated. Under such conditions, unusually large ranges of radar coverage along the surface of the earth may occur.

The radar refractive index gradient in the vertical required to produce such ducts is quite considerable but does occur over limited height ranges. The refractive index of the atmosphere for radar wavelengths depends upon temperature, pressure and humidity. The ducts are generally associated with temperature inversions where the water vapour content decreases rapidly with elevation, *i.e.*, where there is an abnormal moisture lapse rate. The effect of temperature distribution through these layers is of less importance than the moisture distribution. The dependence of the index of refraction on pressure may be neglected. Generally speaking, such conditions are associated with stability in the lower atmosphere and may occur, for example, on a calm winter morning when the change in moisture content is expected to be well pronounced as a result of the ground inversion set up due to the nocturnal radiative cooling. On other occasions, subsidence inversions may also result in duct-formation. Such conditions of radar energy propagation are expected to occur occasionally in all regions and cause the normal super-refraction phenomenon.

One of the effects of super-refraction is that the area, in which super-refraction is occurring and ground clutter are being detected on radarscopes, is rendered useless as far as the detection of radar weather echoes is concerned. Two examples are shown in Figs. 18(a) and 18(b). It is, therefore, very essential that at every radar station, a local study is conducted regarding the time and manner of occurrence of super-refraction echoes as also the ranges covered in such cases.

3. Abnormal super-refraction

However, there are cases of super-refraction occurring under unusual and abnormal conditions such as under a thunderstorm or just after the passage of a thunderstorm. An example is given in Fig. 19. What is actually required for duct-propagation is the creation of temperature and moisture stratification of the required type. The downdrafts and rain from thunderstorm do, on occasions, produce quasi-stable stratifications which are maintained for sometime if the surface wind is calm or very light. Mathur and Kulshrestha (1961) have discussed such situations in detail.

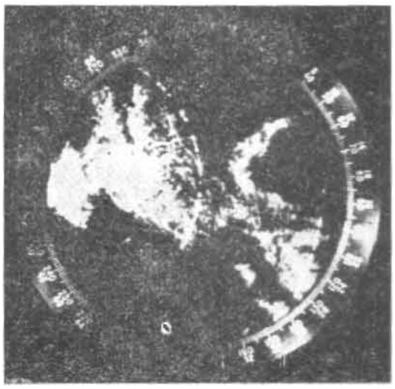

Fig. 19. Abnormal super-refraction

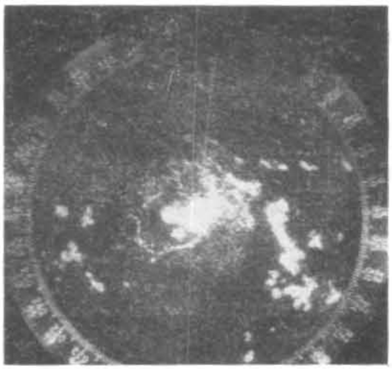

Fig. 20. Ring angels

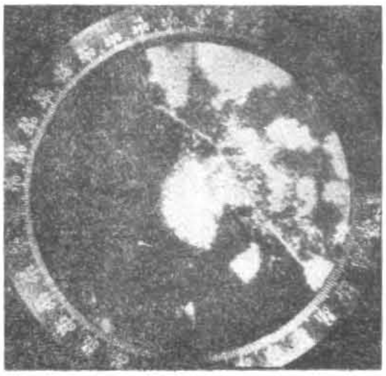

Fig. 21. Thin line angels

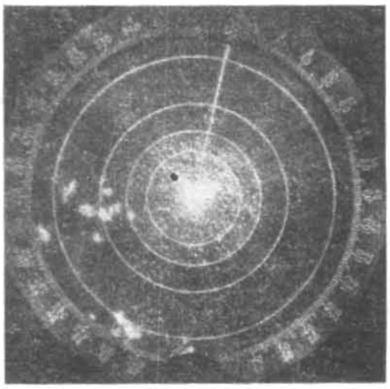

Fig. 22. Blobby angels

It, therefore, follows that even in an unstable atmosphere which is sustaining thunderstorm activity, there are chances of a temporary ducting taking place. This, when it happens, will hamper normal function of storm detection. Luckily such occurrences are short-lived.

4. Ring Angels

Ring angels were first observed on a 23-cm L band radar using MTI (moving target indicator), but they can be detected on smaller wavelengths also at least in tropics where temperature gradients are much more steep. A typical example of ring angels recorded at New Delhi on CPS-9 radar is shown in Fig. 20. The preferred time of occurrence of this type of angels is in the afternoon. There appears to be no correlation of angel occurrence with observed surface weather.

It has been suggested that this type of angels occur due to the reflection of energy from shear gravity waves existing on a surface of density discontinuity. From an examination of the radiosonde observations, it is seen that there usually are temperature inversions of the order of 2°C per 1000 ft at a height of the order of 2000 to 5000 ft above ground. This type of angels, however, appear to be of academic interest only and seem to have no practical operational utility as far as can be judged at present.

5. Squall-precursor (thin line) Angels

The thin line shown in Fig. 21 was about 60 miles in length and was found to move ahead of a large group of strong convective cells and may be described as what has been called a squall-precursor or a first-gust line or a wind-shift line. At the time of the radar photograph, it was still about 10 miles to the northeast of the station and was approaching the station. The station experienced a squall 28 minutes after taking the radar picture shown in Fig. 21. The wind speed, which had been of the order of 10 kmph, developed a lull and thereafter the wind speed suddenly rose to 66 kmph. The squall lasted for only 4 minutes. Thereafter the wind speed again fell to 15 kmph. During the squall, the wind direction shifted from SW to NE. However no rain was recorded. This case has been discussed in detail by Kulshrestha (1961).

For this type of angel activity, as also for other types of angels, there is a controversy about the possible echo sources. These precursor lines, giving Sharp and distinct echoes, are known to be themselves devoid of any scattering particles. It has been suggested that they are either gravity waves or the 'nose' portion of an undercutting front.

This type of angels show great promise of practical use in short-range forecasting of squalls. The only difficulty is that such squall-precursor lines are recorded more frequently and at greater ranges on radars using longer wavelengths; the best detection being on 23-cm wavelength when the precursor line may be detected as much as 50 to 60 miles from the station to enable forewarning of the squall to be issued sufficiently in advance.

6. "Blobby" Angels

During the hot weather months (April to June), radars in tropics record angel echoes having certain peculiar characteristics; the most important amongst them being their apparent association with an upper air temperature inversion or on isothermal layer between 6 and 11 km above ground. It will be seen from the example in Fig. 22 that the appearance of these angels suggests for them the nomenclature of 'blobby' or 'spotty' angels.

The main characteristics of this type of angel activity are:

(*i*) These are angels of a 'blobby' or 'spotty' nature,

(*ii*) These occur during the hot weather months (late April to late June) only,

(*iii*) These occur in the presence of insolation only and are never observed at nights,

(*iv*) The angel activity is more or less equally distributed upto about 25 miles round the station, although on occasions it may extend to about 50 miles. It is mainly limited to the first 5000 ft above ground,

(*v*) The vertical wind profiles show that shear is practically absent on days of such angel activity,

(*vi*) There are always some convective cells present in the neighbourhood, thus characterising the unstable and turbulent nature of the lower atmosphere and

(*vii*) A very significant feature of these angels is the simultaneous occurrence of an upper level temperature inversion or an isothermal layer.

This type of angels have been discussed in detail by Kulshrestha (1962).

Conclusions

In the preceding pages, an attempt has been made to classify the radar weather echoes observed in a tropical region like India. The characteristics of radar weather echoes of various types have been analysed and presented so as to be of help to professional radar-meteorologists in their day-to-day interpretation of radar weather echoes observed in the tropical areas.

The authors have endeavoured to make the classification and the analysis as rational as is possible at present on the basis of the available data. It must be remembered that only a few years of systematic radar observations in various parts of the country are available. Further experience should bring to light many more interesting and useful aspects of radar weather echoes.

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