# AIR MASS STRUCTURE AND THE MECHANISM OF THUNDERSTORMS IN INDIA DURING THE PRE-MONSOON AND POST-MONSOON SEASONS.

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(Communicated by Dr. S. K. Banerji, F.N.I.)

(*Read at the Symposium on 'Atmospheric Processes', held at Bombay, on August 30-31, 1946; received for publication on June 2, 1949.*)

ABSTRACT.

The characteristic features of the air masses which dominate over the country during the two transition periods, viz., from winter to south-west monsoon and *vice versa* are considered with a view to finding out why these two particular seasons favour specially the growth of marked instability in the atmosphere leading to frequent and often severe thunderstorms in India. It is seen that while many of the individual thunderstorms or showers of thundery character in these months are of intra-air mass type and occur in a homogeneous (horizontally) mass of air, being initiated by local surface heating or by a mountain range, widespread thunderstorms of sufficient intensity on the plains are in general the result of development of waves on a quasi-stationary discontinuity where the two main air masses of the season converge towards each other. The process of interaction in the zone of discontinuity however differs fundamentally from what occurs at a normal warm or cold front of the extra-tropical regions, as becomes evident from the distribution of thunderstorms relative to the moist air sector in the two cases. The main zone of thunderstorms moves down the front in the general direction of movement of the air at heights of 3 to 6 km., and although a progressive movement of the thunderstorm field with a certain time sequence is noticed, isochrones are often irregular, and many of the individual storms do not fit in in the general picture of the isolines drawn.

Thunderstorms of destructive violence are more frequent in northern India, and especially in the north-eastern parts of the country, than in South India even though the moist air in the latter area is usually present in a deeper layer. This is due to the fact that the anticyclonically curling and subsiding dry air mass at upper levels at or near the freezing heights, over South India offers a less favourable environment for the vigorous convection of the lower moist air than over northern India.

## INTRODUCTION.

Except during the three months December, January and February, when thunderstorms proper are of rare occurrence and thundery weather develops only very infrequently in certain restricted parts of India, fairly well-marked thunderstorms or rain with thunder can be expected over most of the country during all the other months of the year. Full-fledged storms of destructive violence, with loud peals of thunder, vivid lightning, heavy showers of rain or hail and severe squalls have, however, their own characteristic seasons for development, and these are the pre-monsoon season (April to May), and post-monsoon season (mid-September to mid-November).

The underlying cause of a thunderstorm is the instability of the atmosphere, and the reason why the two seasons of transition preceding and following the south-west monsoon favour specially the growth of marked instability, leading to frequent and often severe thunderstorms in India, becomes fairly apparent when we consider the air masses which prevail over the country during these months.

## AIR MASSES DURING THE PRE-MONSOON PERIOD.

A provisional scheme of classification of air masses in India has been suggested by the writer of this note in a recent publication (Roy, 1946) of the India Meteorological

Department. Judging from the pressure field and the corresponding atmospheric circulation over and around India during April and May, we find that the air in the lower layers which streams across the greater part of this country in these months is the Tropical Continental (Tc) air, with its source region in central and south-west Asia. While it originates as a warm continental air, with low moisture content and fairly stable stratification, it gets largely modified later in course of its circulation over India. While entering north-west India, the Tropical Continental air gets progressively heated in the lower layers and is then caught up in the cyclonic circulation; turbulent mixing ensues, and this together with the surface heating causes the air mass to develop nearly adiabatic lapse rate, with super-adiabatic lapse in the lowest half to one kilometre in afternoons, a condition for instability. Notwithstanding this, well marked hydrometeors rarely occur in this air mass because of its insufficient moisture content. Later, in course of its further circulation, the air from north-west India undergoes yet other important modifications as a result of sea travel before it reaches certain parts of India, viz., the South Peninsula, Bengal and Assam, acquiring characteristics akin to those of Tropical Maritime (Tm) air in the lower layers. The type of air mass usually found over these areas may be designated by the symbol $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$, that is, an air mass with tropical maritime characteristics below and tropical continental characteristics above.

## Main zone of thunderstorm activity.

An examination of the pattern of the mean wind circulation over India (India Met. Deptt., 1943) in the lowest kilometre during April shows that a line running roughly from south-west to north-east, across the North Deccan, Orissa, Bengal and North Assam marks out a demarcation between the Tc air from N.W. and the $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$ air flowing from S. to S.W.'ly direction. It is further seen from the charts giving the distribution of rainfall and frequencies of thunder in the month of April that the zone of maximum rainfall and maximum thunder activity in this month lies more or less along this line of demarcation, indicating that the convergence of the two types of air apparently plays an important part in the thunderstorm development during this month. The features in May are similar to those in the month of April. The picture of the day to day circulation, however, varies, and with it changes the position of the line of convergence of the two air masses, and so also the area of thunderstorms from one day to another. It is possible to indicate in a general way the region of future thunderstorm development if one is able to fix accurately the zone of discontinuity between the two air masses in the first 2 or 3 km. above sea-level, and also to picture roughly the orientation of this line of discontinuity during the period of the forecast. A careful examination of the day to day weather chart reveals that the maximum activity of thunderstorms and rain occurs not exactly on the line of discontinuity, but at a distance of 50 to 100 miles to the moist air side of it, and that both the intensity as well as the density of distribution of the thunderstorms decrease as we move well into the field of the maritime air mass. Again the thunderstorms may not occur systematically all along the discontinuity, and to determine the area which becomes the principal centre of activity, and to predict the relative intensity of the storm in the different areas are the real problems which the forecasters in this season often find it difficult to solve fully.

To understand the mechanism by which the convergence of Tc and $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$ air helps the development of weather in this season, we shall consider in a general way the differences in the physical properties and thermodynamical characteristics of these two air masses. The $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$ air is, as has been mentioned above, but a modified stage of the original Tc air, whose physical properties in the lowest layers have undergone a substantial modification as a result of sea travel. Apart from the more direct effect, viz., an increase in the moisture content up to a certain height, and this depends largely upon the time spent by the air in its sojourn over the sea, there is also the indirect effect of a substantial cooling of the lower layers as a result of humidification. While the dry bulb temperature falls, the air particularly in the lowest layers acquires a higher wet bulb temperature, as a part of the latent heat required to evaporate water into it is drawn from the sea surface. When, under the influence of a favourable pressure field, this cool and humidified air returns landwards and meets the Tc air, it takes the form of a wedge, as shown in Fig. 1, and has a tendency to undercut the latter. It is within this wedge that

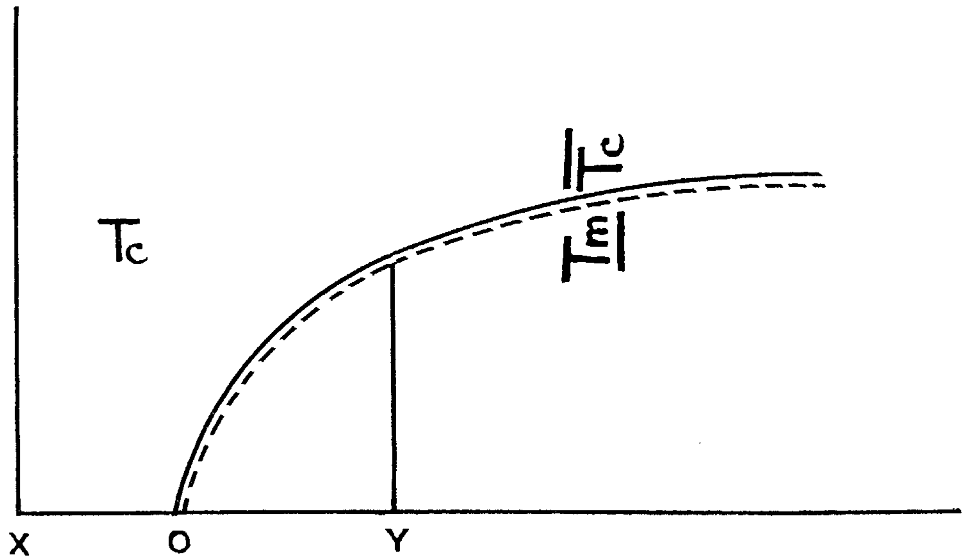


FIG. 1. Vertical Section showing the discontinuity between Tc and $\underline{\text{Tm}}\ \overline{\text{Tc}}$ air during the hot season (April to May).

the thunderstorm activity occurs, and is usually most marked at a short distance from the point *O*, where the Tm air extends to a height of 2 km. or so and is then overrun by Tc air aloft. As we move further away from the zone of convergence and get well within the Tm air mass, the thunderstorm activity usually falls off, in spite of the moisture being present there in a greater depth. Venkiteswaran (Venkiteswaran, 1932) in his study of thunderstorms over the Peninsula arrived at similar conclusions. While the main thunderstorm field for its development thus depends to a large extent on the juxtaposition of the two air masses, Tc and $\underline{\text{Tm}}\ \overline{\text{Tc}}$, the process of interaction in a zone of discontinuity of this kind differs fundamentally from what occurs normally at a warm or cold front of the extra-tropical region, where the humid air being warmer than the drier air mass either glides up the frontal slope or is forced upwards as a result of being undercut by the cold wedge.

In Fig. 2 are shown the D.B. and W.B. curves, plotted on a $T$-$\phi$ diagram, in respect of Tc and $\underline{\text{Tm}}\ \overline{\text{Tc}}$ air over stations *X* and *Y* respectively on the two sides of the surface of discontinuity in Fig. 1. The D.B. curve *ABCD* of the Tc air shows nearly adiabatic lapse rate up to a considerable height, while the W.B. curve *A'B'C'D'* shows a lapse rate exceeding the saturation adiabatic. In spite of the convective instability in the air, its markedly low humidity, as indicated by the

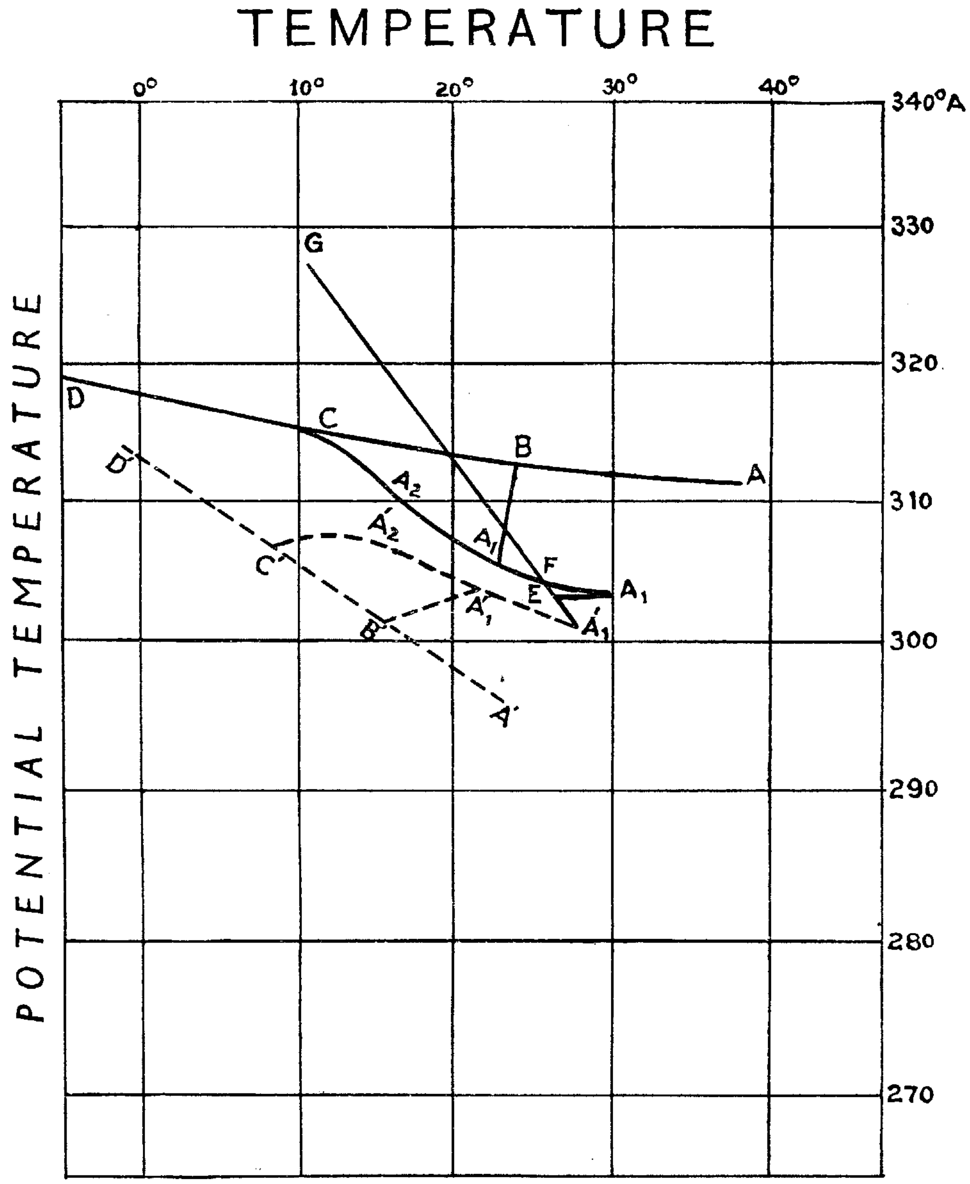


FIG. 2. D.B. and W.B. curves relating to Tc and Tm $\overline{\mathrm{Tc}}$ air, plotted on a $T$-$\phi$ diagram.

large separation between the D.B. and W.B. curves precludes the possibility of the energy of instability being realized and manifesting itself in the form of weather. Two other sets of curves (1) $A_1A_1$ $BCD$ and $A'_1A'_1$ $B'C'D'$ and (2) $A_1A_1A_2$ $CD$ and $A'_1A'_1A'_2$ $C'D'$ shown in the figure represent respectively the D.B. and W.B. curves of Tm $\overline{\mathrm{Tc}}$ air, with Tm characteristics extending to a height of about 1 km. only in one case, and up to 2·5 km. in the other. A large fall in dry bulb and a good rise in wet bulb temperatures cause the convective condensation level of the surface air to be brought down to quite a small height above ground, and a supply of relatively small external energy becomes sufficient to bring about condensation and the formation of convective types of clouds. Owing, however, to the markedly stable stratification in the inversion layer $A_1$ $B$, which exists in the first case, separating the cooled and humidified air in the lowest one kilometre from the warm dry Tc air above, no weather of significance usually develops when the Tm air is shallow. The situation, however, is different in Tm $\overline{\text{Tc}}$ air with a superposition as in the second case. The surface air, on being helped to ascend to a small height of about half a kilometre, attains saturation at $E$, and in course of its further journey upwards acquires temperatures as shown by the curve $EFG$. At all heights above $F$ the temperature of the rising saturated air being higher than that of the surrounding air, the parcel after reaching the height $F$ shoots upwards through the environment, releasing a considerable amount of energy in the process. Latent instability of the real type, as defined by Normand (Normand, 1938), is thus present in a marked manner in the air mass under consideration. All that is needed to initiate a large scale convection is the supply of a suitable trigger to help the ascent of the ground air up to the point $F$, and if this is available, the energy of instability which is present in a latent form, is realized at later stages, and reveals itself in the shape of tall convective clouds, showers of rain, and also thunderstorms or hailstorms if the convection happens to be sufficiently vigorous. The rise in wet bulb temperature in the lower humid layer, aided by high lapse rate which prevails at higher levels, thus gives the Tc air, after it has had a fairly long history of oceanic travel, a thermodynamical structure which is substantially different from that of the original Tc air mass. Strong insolation in this region, to which the surface air is subjected during the day provides a trigger to initiate the convective movement in the Tm $\overline{\text{Tc}}$ air mass, but this by itself is usually not sufficient to wipe off or push the moist air up through the layer of inversion, which is quite deep when the Tm air below is shallow. The result of this is that in an area which is simply overrun by homogeneous Tm $\overline{\text{Tc}}$ air, no more than thundery weather with Cu and Cb clouds in afternoon and perhaps a few thunderstorms of insolational type at places can ordinarily be expected unless other favourable factors can help to provide the balance of energy required to push the moist air through the lower layers of the environment of latent instability. In general, over the plains, in order that thunderstorms of sufficient intensity may occur and have a fairly general distribution in any area, it is necessary that convergence of some kind should provide in a sustained manner, irrespective of the hour of the day, the necessary energy of trigger for the convection of moist air through the lower layers.

## Conditions favourable for growth of active thunderstorms field.

As has been mentioned earlier, on a normal 0·5 or 1 km. chart in April (Fig. 3) the trough line running S.W. to N.E. from the North Deccan to Assam is a line of convergence between the Tc and Tm $\overline{\text{Tc}}$ air. Normally, the Tm characteristics in the latter air mass extend to a height of only 1 km. or less, and the store of energy which is ultimately derivable from the latent heat of water vapour being small, no well-marked weather features ordinarily develop along and near this discontinuity. Further, on such a chart, the discontinuity in physical properties between the N.W.'ly to W.'ly air current and the W.'ly to S.W.'ly air is often not a sharp one, the dry air in the former field only acquiring progressively more and more maritime characteristics as it gets into the zone where the south-westerlies prevail. Also, normally, the discontinuity line is a fairly smooth curve, except where it passes across mountainous regions and, as such, the two air currents flow side by

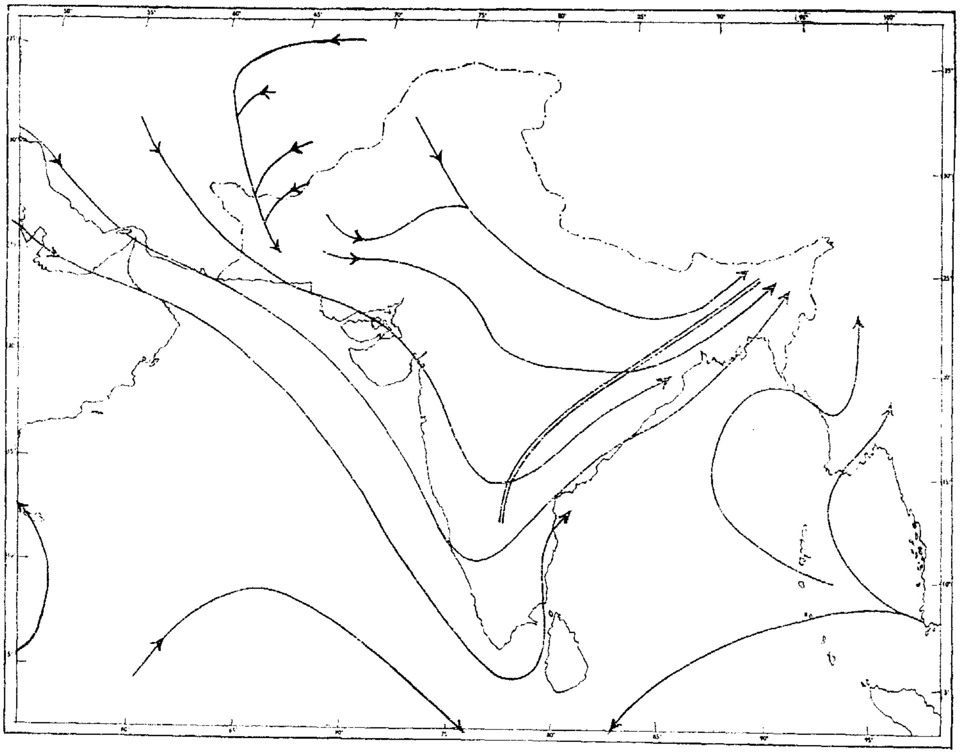

FIG. 3. Stream lines showing the normal air movement in the layer 0·5 to 1 km. above sea-level over India and neighbourhood in the month of April. The double line represents the discontinuity between Tc and $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$ air.

side without the horizontal movement of either of these being interfered with or checked by the other stream. The seasonal trough of low, or part thereof is, however, accentuated at times by more intense heating than usual, or as the result of passage of a western disturbance or its secondary across the area, and it is in these circumstances that the conditions become really favourable for the growth of well-marked thunderstorm fields, for reasons mentioned below:—

(i) The intensification of the low causes the moist air to be drawn into the area in a deeper layer than usual, and also from more southerly latitude where the Tm characteristics are better developed;

(ii) the convergence between the Tc and $\underline{\mathrm{Tm}}\,\overline{\mathrm{Tc}}$ air is more marked in the region of falling pressure;

(iii) the current of dry air in the upper levels in the rear of the eastward moving surface low is stronger than usual, and being more fresh in its source characteristics is colder than normally. The process of convection of the lower moist air through the environment is more vigorous and the thunderstorms are, therefore, more intense.

### DEVELOPMENT OF WAVES ON CONVERGENCE FRONT.

Fig. 4 shows the pattern of the stream lines of air at 1 to 2 km. on a day on which a well-marked secondary of a western disturbance has moved into the seasonal trough over northern India, and lies over the West U.P. and West C.I., with its centre near Jhansi. Under the influence of this secondary, the air in the Tm $\overline{\text{Tc}}$ sector has been drawn north-westwards across the central parts of the country, and the normally smoothly running line of discontinuity now shows a prominent tongue-like protuberance where marked convergence is taking place between the two air masses. In addition, the discontinuity line shows some small wave-like distortions at a few other points, arising out of orographic or other local influences. In the zone, marked *A*, at the end of the tongue of moist air advancing towards

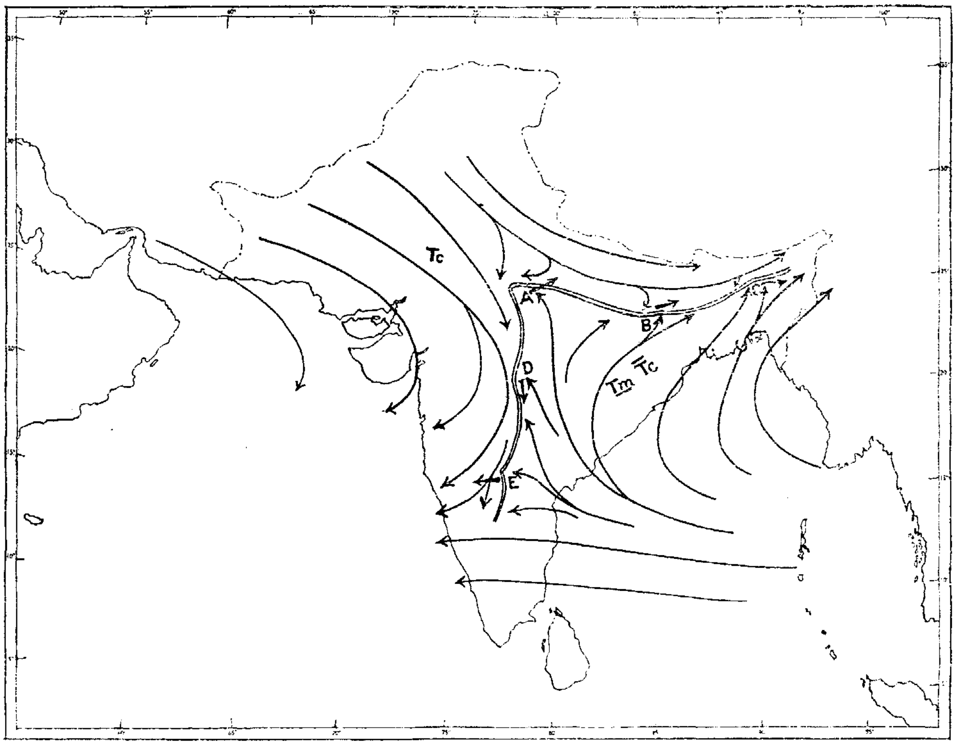


FIG. 4. Stream lines of air at 1 to 2 km. on a day in April with a well marked secondary centred near Jhansi. The discontinuity between Tc and Tm $\overline{\text{Tc}}$ shows sinuosities at *B*, *C*, *D*, and *E*, in addition to the prominent tongue like protuberance at *A*.

Jhansi, the Tm air in the lower layers is very nearly trapped by the Tc air flowing in from different directions, and being thus forced to rise, gets the necessary initial lift required for the ultimate realization of the energy of latent instability present in the system. While the area *A* thus develops into the main zone of thunderstorms and rain on this day, the more limited convergence near the smaller distortions on the discontinuity at *B*, *C*, *D* and *E*, aided by insolation during day, favours the growth of subsidiary thunderstorm fields, particularly in afternoon/evening. The movement of the principal thunderstorm field *A* is determined largely by the future movement of the depression near Jhansi, as in the case of frontal thunderstorms associated with an extratropical depression. A closer examination, however, reveals that in points of detail, the part played by the air mass discontinuity in the above case, is very different from that in truly frontal thunderstorms, and this becomes evident from the distribution of thunderstorms relative to the moist air sector in the two cases. While the frontal thunderstorms associated with an extratropical depression lie more or less in a line along and near the fronts (Fig. 5*a*) and move approximately in a direction normal to the front,

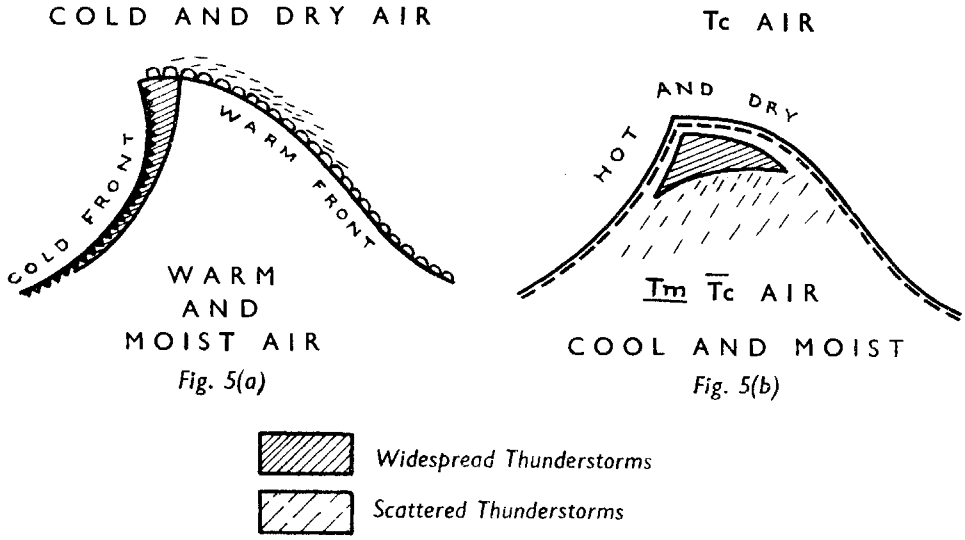


FIG. 5(*a*). Cold and Warm fronts associated with extra-tropical depressions.

FIG. 5(*b*). Wave structure on the discontinuity between Tc and $\underline{\text{Tm}}\,\overline{\text{Tc}}$ air over India in April.

the thunderstorms in the present case, as in Fig. 5(*b*), develop within the moist air tongue and show much less regularity in their distribution, and in this respect are more in the nature of thunderstorms of intra-air mass type.

In the above example, the secondary depression near Jhansi, by providing the main mechanism for convergence, caused the development of a prominent bulge or a wave of large amplitude in the pre-existing smoothly running line of discontinuity between two air masses. For development of such waves and of thunderstorms in association with them, it is however not essential that a well-formed depression should be present in each and every case, as these may be caused by other influences of a more localized character, such as, orographic convergence, inequal pressure variations in two adjacent zones within a low pressure trough due to differential diurnal heating or other causes.

Let us consider a day in April on which an extended trough of low lies over the central parts of the country with its trough line running from N.E. to S.W. In certain circumstances, this line may represent a sharp enough discontinuity, separating the N.'ly to N.E.'ly Tc air from S.'ly to S.W.'ly air of the $\underline{\text{Tm}}\,\overline{\text{Tc}}$ type. The way in which the two opposing streams react on each other as a result of such a juxtaposition will, in general, be not quite uniform all along the line of discontinuity. While at some points the moist air mass will have a tendency to encroach into the zone previously occupied by the dry air, the tendency in the neighbouring areas will be for the dry air to push forward within the moist air sector. The result will thus be some kind of a wave development on the original discontinuity line, as in Fig. 6. Within the bulges as at $A_1$, $A_2$ and $A_3$, where the northward moving $\underline{\text{Tm}}\,\overline{\text{Tc}}$ air turns towards the direction in which the Tc air lies, the moist air stream will develop a cyclonic vorticity. On the other side of the discontinuity opposite to the points $A_1$, $A_2$, $A_3$ the southward flowing Tc air mass on being pushed westwards by the surge forward of the moist air will acquire an anticyclonic curl. In the neighbouring zones $B_1$ and $B_2$, where the bulges are in the opposite direction, cyclonic vorticities will develop in the Tc air stream. Within the bulge $A_2$, where convergence is most pronounced and the amplitude of wave displacement is maximum, and also to a lesser extent within $A_1$ and $A_3$, the cyclonic convergence will help to provide the moist air with the necessary trigger for its convecion upw ards, and thunderstorms will develop more readily than in the neighouring zo nes opposite to $B_1$, $B_2$, $B_3$. The direction in which the principal thunder-

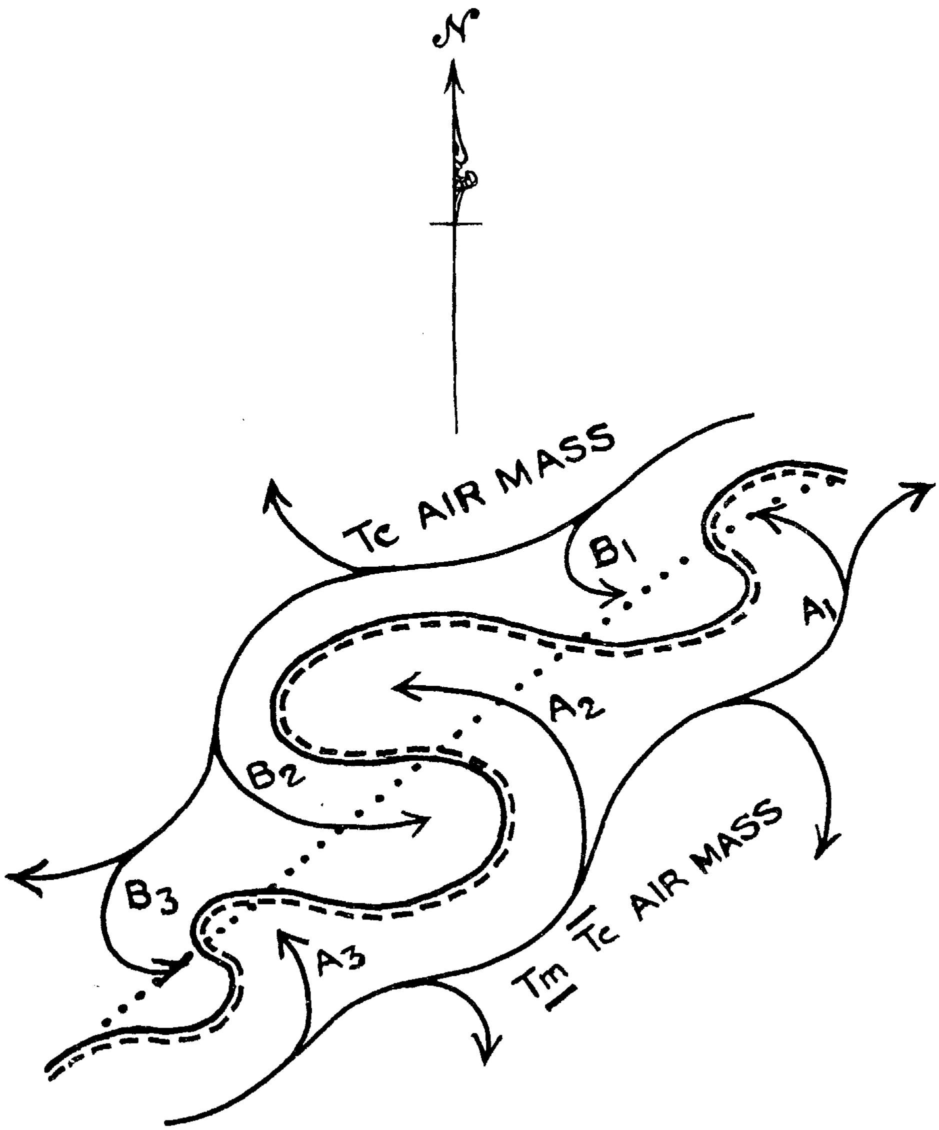


FIG. 6. Shows wave development on a discontinuity, running N.E. to S.W. between Tc and Tm Tc air masses. The single dotted line indicates the position of the discontinuity prior to the wave disturbance.

storm field at $A_2$ will move in course of time will depend upon the future orientation of the wave pattern and this will be determined largely by the way in which the overturning of the column of air occurs as a result of the thunderstorms. In general, we should expect the wave pattern to move down the front in the general direction of movement of the air at heights of 4 to 6 km., the levels from which the compensating downward currents usually start. Of the five thunderstorm fields, indicated in Fig. 4, the main one at $A$ is likely to move east or north-eastwards, that is, the direction in which the secondary depression usually moves in this season. The way the other subsidiary fields at $B$, $C$, $D$, and $E$ will move will depend upon the upper air flow over the respective areas, and taking into consideration the most probable flow pattern of air at 3 to 6 km., the directions of movement are expected to be as indicated by the arrows in each case.

Often in the month of April or May, we find a well-marked discontinuity line, separating Tc and $\underline{\text{Tm}}$ $\overline{\text{Tc}}$ air masses, without any wave pattern being prominently noticeable on the synoptic chart. Slight sinuosities or waves of small amplitude may exist or develop temporarily and lead to the formation of thunderstorm vortices within the moist air sector, close to the discontinuity line. These thunderstorm cells, after development, sometimes show a progressive movement in a direction which is determined by a number of factors, the chief of which, as mentioned above, is the flow pattern of air at upper levels. The sequence of thunderstorms belonging to each series depends upon the conditions which prevail in the different systems, and the associated features are more in the nature of non-frontal thunderstorms, as discussed by Byers (Byers, 1942). An attempt to draw isochrones, taking into account thunderstorms belonging to the different series often fails, and we see considerable irregularity in the lines drawn. This becomes further complicated by the fact that some of the storms may develop well within the moist air sector, without having to depend in any way on the air mass discontinuity, and some may be of the secondary type in which the moist air is forced upwards by the advancing wedge of the rain-chilled subsiding air from a primary or parent thunderstorm, which itself may not be of discontinuity origin.

One interesting feature which is noticed sometimes, while studying the progressive movement of a thunderstorm field is the apparent oscillatory movement of a weak low with which the thunderstorms are associated. With the overturning of the air column following the occurrence of thunderstorms, the wavelike structure on the quasi-stationary discontinuity shifts progressively, and the low or part thereof, close to the crest of the wave, apparently gets filled up or is seen to move down the discontinuity along with the thunderstorm field. The sequence goes on, so long as the process of overturning of the atmosphere as a result of instability continues. In a weak low the effect of cyclonic convergence alone may not be sufficient to provide the required trigger energy for initiation of a thunderstorm, and some additional assistance, such as insolation may be necessary. The sequence of thunderstorms and consequent rolling process of the atmosphere may, therefore, cease in such cases sometime after the evening, when the horizontal flow of the air at each level, undisturbed by large scale vertical movements, may once again be established. As a result, by the following morning, the weak low of the previous day, with its associated flow pattern of air may sometimes reappear in more or less its original position, and give rise to a fresh sequence of thunderstorms on that afternoon or evening. A shift back to its original position of a low which is principally of dynamic origin is to be expected if the thunderstorm activity does not result in any vital change in the major horizontal flow pattern of the air with which the low is associated. It is the experience of the writer that this feature of weather process is by no means uncommon and should be remembered before an improvement of weather on the next day is forecasted on the ground that the afternoon chart of the day shows that the low which gave rise to the thunderstorms has moved away from the area.

Hitherto we have considered only the two air masses Tc and $\underline{\text{Tm}}\,\overline{\text{Tc}}$, and the thunderstorms which develop in the latter air mass close to the discontinuity between the two. Although these are the air masses which are more commonly found over India during the pre-monsoon season, and the development of thunderstorms occurs more frequently under conditions as discussed above, we may have thunderstorms originating in other types of air masses also, and the mechanism of their development may also be substantially different in some cases. For instance, we sometimes have over the central and south Bay of Bengal Tropical Maritime (Tm) air up to a good height, reaching the area from the east under the influence of low pressure waves from the China Seas. With the westward movement of these lows, some of which develop into a depression over the South Bay, Tm air sometimes advances into the South Peninsula and occasionally reaches the Deccan and the central parts of the country. In addition to the thunderstorms which frequently develop in this Tm air mass, especially in association with depressions, we sometimes have thunderstorms of real frontal type, to the west or north-west of the depression where the Tm air in a deep layer meets the Tc or $\underline{\text{Tm}}\,\overline{\text{Tc}}$ air. Again, occasionally during this season, and particularly in April, Transitional Polar Continental (Pc Tc) air of the winter type invades northern India in the rear of active western disturbances, and while advancing down the Gangetic Valley sometimes develops a well-marked cold front on meeting the $\underline{\text{Tm}}\,\overline{\text{Tc}}$ to the east or south-east. Some of the severe hailstorms of the season, and thunderstorms during late night or early morning are caused by the frontal action of this advancing extra-tropical air.

Thunderstorms of destructive violence are more frequent in this season in north-east India, viz., Bengal and Assam, than in South India, even though moist air in a deeper layer is usually present in the latter area. This is due to the fact that the anticyclonically curling and subsiding dry air stream at upper levels by the time it reaches South India becomes distinctly warmer than the Tc air at the same level over northern India, and thus offers a less favourable environment for the vigorous convection of the lower moist air than over northern India.

## Thunderstorm of the post-monsoon season.

In its essential features, the mechanism governing the development of thunderstorms in the post-monsoon season is usually very similar to that in the pre-monsoon months. Apart from the intra-airmass type thunderstorms in Em or EmT air within the monsoon trough, which by October recedes to the South Bay of Bengal, the South Peninsula and the south-east Arabian Sea, well-marked thunderstorm fields frequently develop to the north-west and west of the trough along and near the discontinuity between Tc and $\underline{\text{Tm}}\,\overline{\text{Tc}}$ air. The air mass structure over the area of thunderstorms is of a superposed type, as in the pre-monsoon season with EmT or Tm air up to 2 km. or so being overrun by Tc air at higher levels, and the underlying cause of thunderstorms is again the instability which arises out of such a superposition. As a rule, during October, the nature of interaction of the air masses near the discontinuity is also similar to that in the pre-monsoon months, the Tc air being as warm as or slightly warmer than the EmT air up to a height of about 2 km. At higher levels during October, and at all heights in November, the dry sector air is usually colder than the air in the moist sector, and the interaction of air masses near the discontinuity at such heights is often of a frontal type. One other important point of difference in the process which leads to thunderstorms in the two seasons is that, whereas in the pre-monsoon months a northward incursion of maritime or semi-maritime air at lower levels into an area where continental air mass prevails leads to the growth of instability, it is the rapid spreading southwards of cold dry air over an area with moist air mass below which favours the development of well-marked thunderstorm fields in the post-monsoon season.

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