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A review of some upper air analyses in relation to prediction of Nor'westers

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ABSTRACT. Standard upper air analyses, such as delineation of thermal thickness patterns on isobaric surfaces, computation of 'development', vertical component of absolute vorticity of geostrophic winds and horizontal wind velocity convergence were made in relation to the nor'wester thunderstorms over northeast India and East Pakistan. For the thickness analysis, the special Dine's meteorograph observations taken in April 1944 at shorter intervals of time and from a closer network of stations than in 1953 were used, while all the above-mentioned analysis were made for eight *consecutive* days in May 1953. No significant medium-range *prognostic value* was found in any of the analyses based on the available network of radiosonde and upper wind data for forecasting the nor'westers 12 to 36 hours ahead of their actual occurrence. Nevertheless, the *partial* thickness patterns of the 700/500 mb-layer, the field of 'development' and the lower level wind velocity convergence, based on the evening data for a particular day, appeared to influence the nor'wester development on the *same evening and night.*

1. Introduction

Of all weather phenomena, there is none so welcome, yet so much dreaded, by the people of Bengal, as the summer thunderstorms of northeast India, popularly called the Nor'westers or *Kalbaisakhis*—welcome because they bring the much needed relief after a hot sultry day and provide rain so beneficial for the crops and dreaded because of their destructive violence. One of the most important phases of weather forecasting in India has, therefore, been to develop such technical aids as will enable the meteorologist to forewarn the public with some degree of confidence, about the time and place of occurrence, severity and approximate track of these storms. A number of studies about the nor'westers have been made. Notable among them are Das (1933), Sen (1931), Normand (1935), Desai and Mull (1938), Sur and Chatterji (1938), Ramanathan and Ramakrishnan (1938), Malurkar (1949) and Roy (1949). It is, however, quite clear from the literature so far available, that the best which the meteorologist has so far been able to do, from an analysis of thermodynamic diagrams, the surface synoptic charts and the lower tropospheric wind circulation patterns on a particular day, is to forecast the conditions under which nor'westers are possible over a certain large region, without any specific suggestions as to the exact time and place of outbreak, intensity and track.

As the thunderstorms are characterised by marked instability and are highly localised in nature, it was believed that they could be treated quantitatively from thermodynamic consideration of the buoyancy forces in an atmosphere in labile equilibrium. Attention was accordingly bestowed upon the analysis of upper air soundings plotted on thermodynamic diagrams, for assessing the extent and nature of convection and the possibility of local development of thunderstorms resulting therefrom. The parcel method and later the slice method were tried with the hope of finding a quantitative aid to thunderstorm forecasting. A little experience of working with these diagrams, however, made it very clear that this tool alone was insufficient for the purpose, since other causes of atmospheric instability, which also contributed to the thunderstorm could not be foreseen from them. The analysis of synoptic surface and upper air charts has, therefore, been the chief aid for nor'wester forecasting. In a review of the existing ideas about the mechanism and the factors for the prediction of nor'westers, which are chiefly based on the contributions by Sur and Chatterji (1938) and Desai and Mull (1938), Newton (1951) has fortified the validity of these principles by adducing evidence obtained by Byers and Braham (1949) in their studies of the thunderstorms of Ohio and Florida.

In recent years, meteorologists have in addition to the above analyses, given their attention to detailed studies of upper air charts, for finding some prognostic factor or factors for thunderstorm forecasting. Namias (1940) introduced the isentropic chart, suggesting that one of the factors for the occurrence of thunderstorms was the presence of a moist 'tongue' on an isentropic surface corresponding to a potential temperature of nearly 315°A. For a successful application of this method of analysis, the availability of reliable upper air humidity data over the isentropic surface was very essential. Owing to the fact that atmospheric processes are often considerably non-adiabatic in nature and that reliable humidity observations are not available, the isentropic analysis is not likely to yield the desired result; in fact, this analysis did not prove fruitful in India.

Douglas (1947) and Ratcliffe (1950) have pointed out the importance of cold pool or trough delineated by the 'total' thickness patterns of the 1000/500-mb layer for inducing instability type of weather. Very recently, Ramaswamy and Bose (1953) also have suggested the association of nor'wester activity on a particular day with the cold pool or trough indicated by the 'partial' thickness patterns of the 700/500-mb layer and presumably also aloft, on the upper air isobaric charts of the previous afternoon. The fact that advection or existence of colder air in the upper and middle troposphere, as revealed by the presence of either a travelling or a stationary thermal trough or pool in the 700/500-mb layer and aloft, will aid thermal instability is understandable. That a mass of relatively cold air over the surface, indicated by the trough or pool in the 1000/500-mb layer thickness patterns will initiate instability by surface heating, is also equally understandable. The question, however, arises whether this kind of analysis of thickness patterns can give the tool for forecasting the localised thunderstorms, in space and time, as distinct from giving an insight into the physical conditions which induce them.

The special aim of this study is, therefore, to find out whether some of the well-known standard methods of upper air analysis would yield some reliable parameter or parameters for forecasting the nor'wester thunderstorms, sufficiently ahead of their occurrence. For this purpose the thermodynamical characteristics of the thickness patterns are studied for a few consecutive days. A few other new methods of upper air analysis, *viz.*, computation of 'development' (Sutcliffe 1947, Sutcliffe and Forsdyke 1950), and velocity convergence (Bellamy 1949) and vertical component of absolute vorticity (Cressman 1953) which are readily adaptable into routine forecasting techniques, are also examined. All the above-mentioned analysis are made using all the available radiosonde and upper wind data for all the days during the period 1 to 8 May 1953, which was characterised by violent thunderstorms and squalls on some days and no thundery activity on the other days, especially over Calcutta (Table 1). During April-May 1944, special Dine's meteorograph ascents were made at shorter intervals and from a closer network of stations in West Bengal and East Pakistan, in connection with the nor'wester investigation sponsored by the India Meteorological Department. These data have been primarily utilised for the analysis of the thickness patterns alone, since the upper wind observations corresponding to these ascents were very meagre.

2. Thickness patterns on isobaric surfaces

(*A*) *Thermal patterns based on data for April 1944*—The Dine's meteorograph data available for the period 17 April to 2 May 1944 were used for primary study of the thickness patterns on isobaric surfaces, as it was felt, that the upper air analysis based on these data would give detailed and conclusive information about the existence, persistence, movement and diurnal variation of intensity of the thermal systems over the region and their role in influencing the thermal instability conditions on days of actual development of thunderstorms. Although, relevant wind data at the appropriate heights were not available for this period, it was considered that the density of the available upper air soundings was sufficient for fixing the patterns of the thermal systems, over the region concerned, rather uniquely.

TABLE 1

DATE	BARRACKPORE	DUM DUM	ALIPORE
1.5.53		∞ $\frac{0710}{0845}$	
2.5.53	☈ $\frac{1635}{}$ ∧ $\frac{1646}{1650}$ ☈̇ $\frac{1650}{}$ ∧ $\frac{1700}{1715}$ ☈̇ $\frac{}{1945}$ ⚡ $\frac{}{2110}$	∧ $\frac{1720}{1725}$ (NW 62 mph) ☈̇ $\frac{1705}{1730}$ ☈̇ $\frac{}{1930}$ •• $\frac{1730}{1940}$	• $\frac{1350}{1425}$ ∧ $\frac{1712}{1742}$ (NW 47 mph) ⁘ $\frac{1717}{1737}$ ☈ $\frac{1730}{2034}$
3.5.53	∞ $\frac{0400}{0510}$		• $\frac{1317}{1322}$
4.5.53	•∧ $\frac{1322}{1326}$ ☈ $\frac{1345}{1530}$ ☈ $\frac{1658}{}$ ☈̇ $\frac{1748}{2118}$ ⚡ $\frac{}{2145}$	☈ $\frac{1335}{}$ • $\frac{1410}{1520}$ ∧ $\frac{1350}{1410}$ (NNE 53 mph) ☈ $\frac{1740}{}$ ∧ $\frac{2045}{}$ • $\frac{}{2205}$	• $\frac{1318}{1324}$ ∧ $\frac{1354}{1409}$ •• $\frac{1407}{1522}$ ☈̇ $\frac{1712}{1730}$ •• $\frac{1730}{2107}$ ☈ $\frac{1730}{2037}$ (44mph) ∧ $\frac{2020}{2045}$
5.5.53	∞ $\frac{0500}{0640}$	⚡ $\frac{1910}{1940}$	
6.5.53	⚡ $\frac{1800}{}$ ∧ $\frac{1830}{1833}$ ☈̇ $\frac{1845}{}$ ∧ $\frac{1900}{1952}$ ☈̇ $\frac{}{2315}$	• $\frac{0020}{0030}$ ☈̇ $\frac{1825}{2346}$ ∧ $\frac{1843}{1900}$ (NW64 mph)	∧ $\frac{1817}{1842}$ (70 mph) ☈ $\frac{1837}{2107}$
7.5.53	⚡ $\frac{1935}{2017}$		
8.5.53	☈ $\frac{0905}{1050}$	∧ $\frac{1030}{1032}$ (NE 37 mph)	☈ $\frac{1320}{1627}$ • $\frac{1352}{1356}$ • $\frac{1553}{1611}$
9.5.53	☈ $\frac{1615}{}$ ∧ $\frac{1710}{}$ ☈̇ $\frac{1715}{}$ ∧ $\frac{1725}{1730}$ △☈ $\frac{1725}{1738}$ $\frac{}{1920}$ ⚡ $\frac{}{2010}$	☈ $\frac{1610}{1630}$ ☈̈ $\frac{1640}{1730}$ ∧ $\frac{1700}{1730}$ (NW 86 mph) ☈ $\frac{1730}{2120}$	☈ $\frac{1608}{}$ ∧ $\frac{1714}{}$ (40mph) ▽ $\frac{1723}{}$ ∧ $\frac{}{1732}$ ☈ $\frac{}{1847}$ ☈ $\frac{0102}{0137}$

The charts of 'total' thickness patterns (1000/500 mb) and the 'partial' thickness patterns (700/500 mb), using the data of these ascents and of the then synchronous radiosondes in and near the region for the period 23 to 29 April 1944 are shown in Fig. 1 (pp. 8-11). The total and partial thickness lines are drawn in full and dotted lines respectively at intervals of 100 feet. The stations for which data, for drawing the patterns, were available are shown by circles.

It will be seen from these figures that—

(*i*) the total thickness patterns show the following features—

(*a*) These patterns appear to be more or less semi-permanent seasonal features of the upper air over northeast India; their depth however, varies appreciably even in the course of 6 to 12 hours (Fig. 1, E to I, K to O).

(*b*) The movement of the thermal systems (troughs, ridges or pools) does not seem to obey the principle of geostrophic or cyclostrophic transport of the thickness lines, as can be judged from the average wind flow patterns at the appropriate levels over the region.

(*c*) The intensity or depth of the thermal systems appears to bear no significant relation to the development of thunderstorms during the following 12 to 36 hours (Fig. 2). Figs. 2(d) and 2(e) are particularly illustrative of the fact that very little nor'wester activity occurred over the region of pronounced cold trough observed in Fig. 1(H); while fairly widespread and active thunderstorms accompanied—Figs. 2(a) and 2(b)—a comparatively weak thermal system observed in Fig. 1(A).

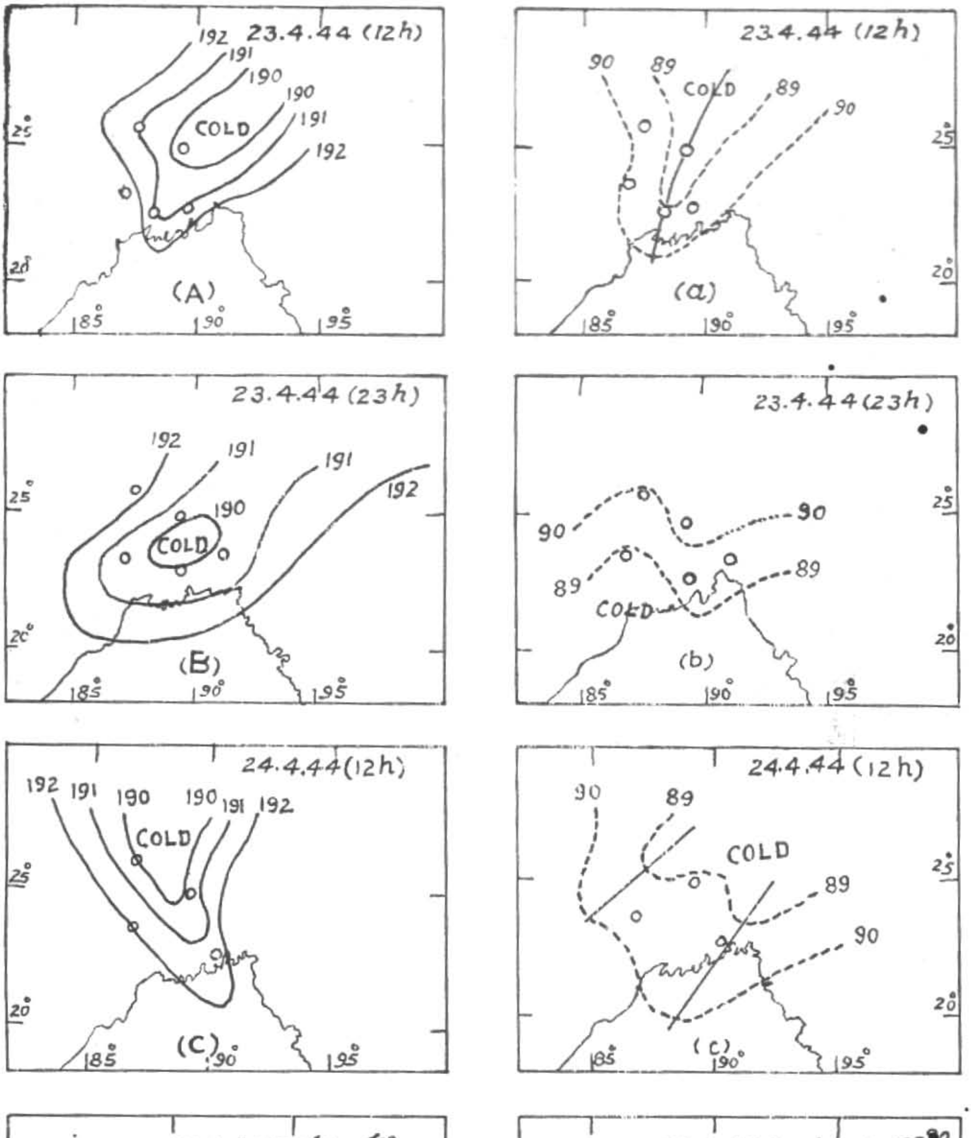
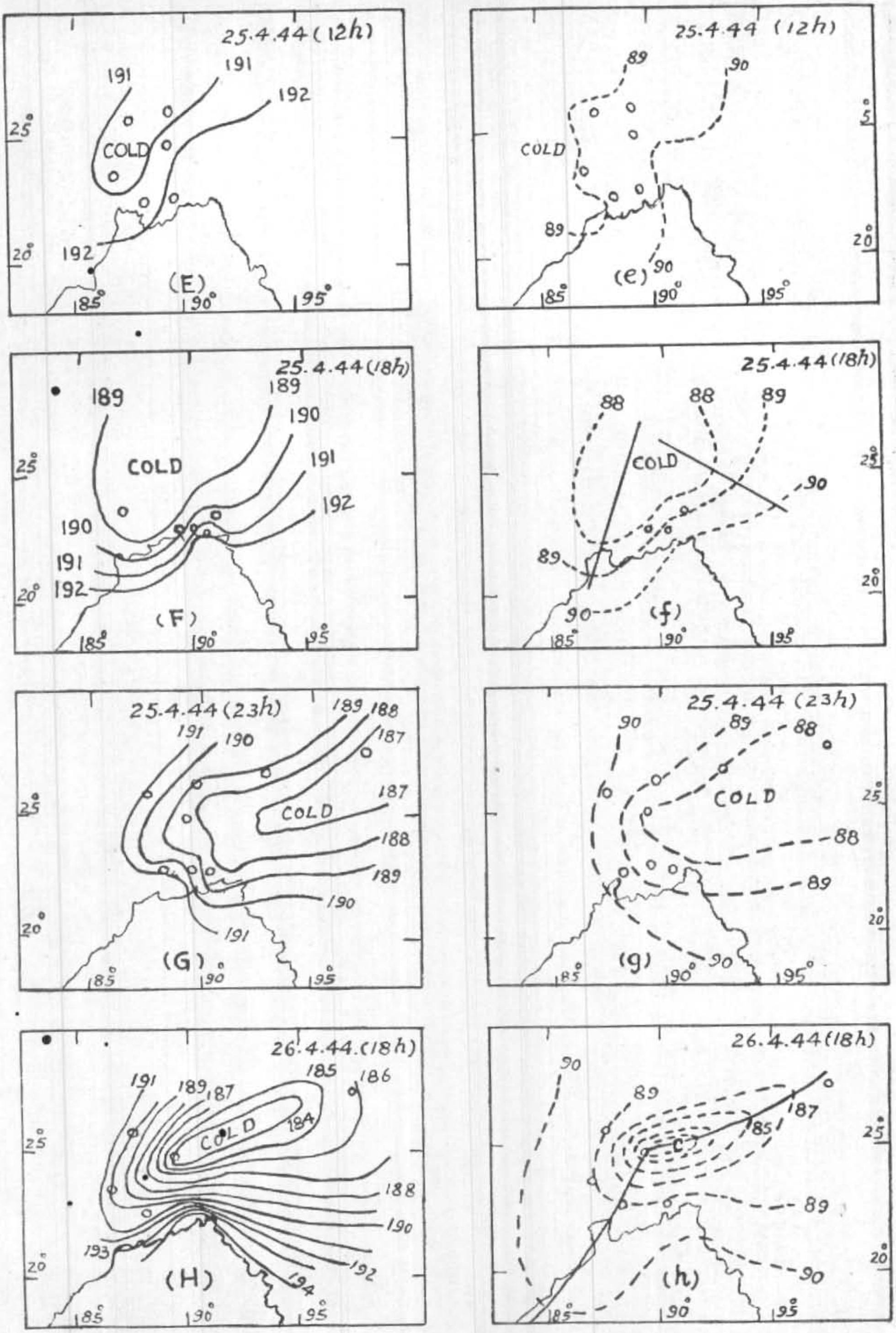


Fig. 1. Total and partial thickness patterns

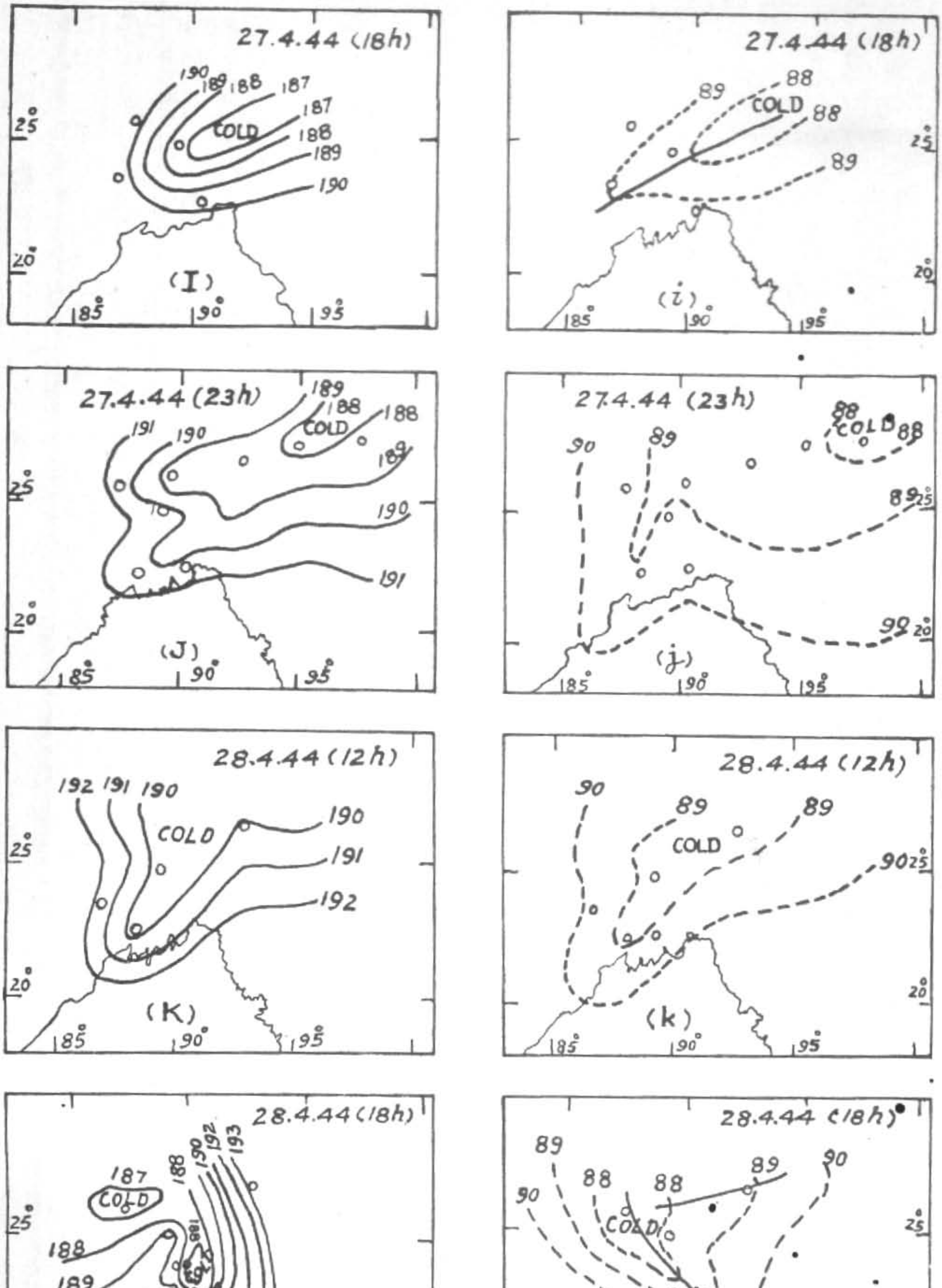
(Isopleths of the total and partial thicknesses are drawn
Only those axes of the cold thermal troughs of the partial thickness



for the period 23 to 26 April 1944

in full and dotted lines respectively, at intervals of 100 ft

patterns are marked in full lines which are indicated on the charts in Fig. 2)



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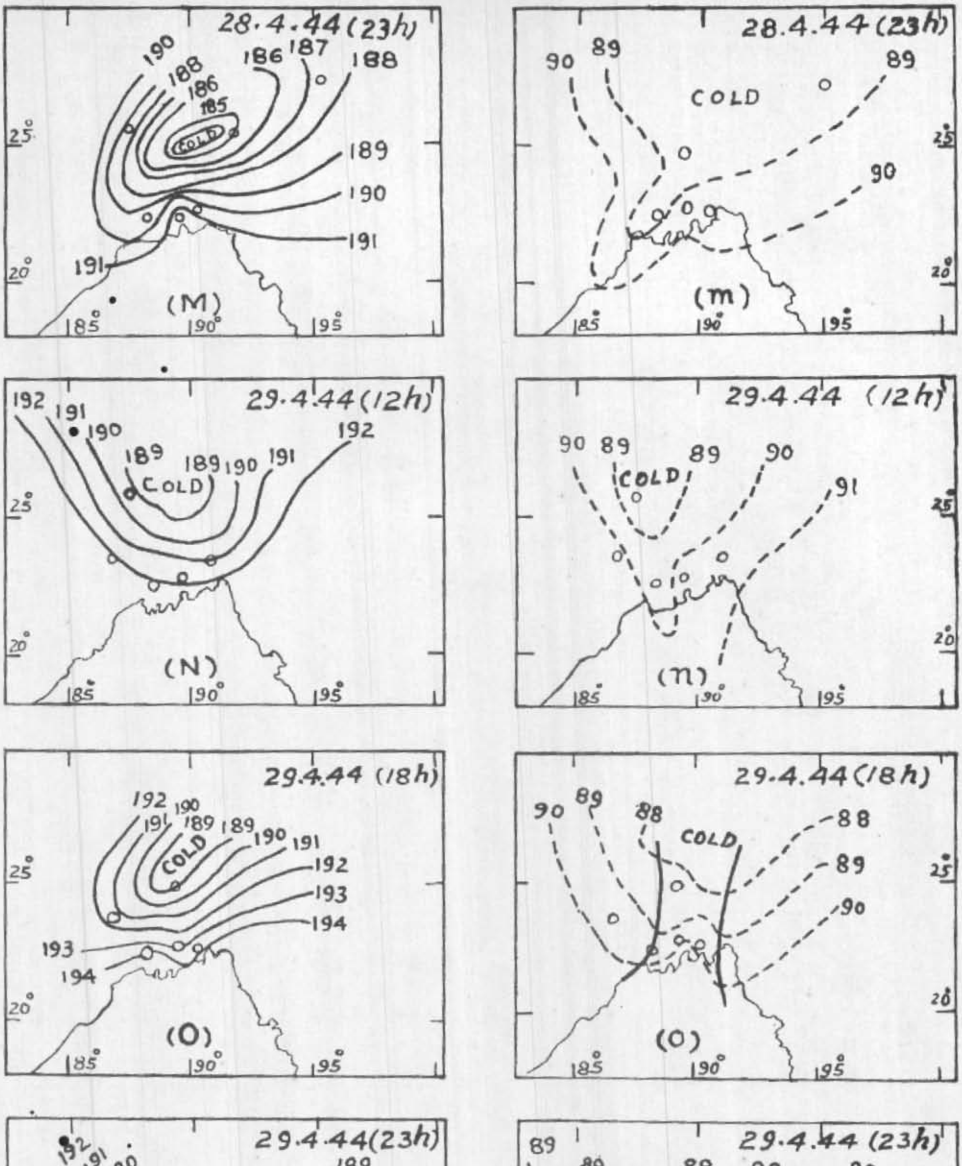


for the period 27 to 29 April 1944

in full and dotted lines respectively, at intervals of 100 ft.

patterns are marked in full lines which are indicated on the charts in Fig. 2) (*ii*) The partial thermal systems show the following features—

(*a*) The thermal system delineated by the partial thicknesses within the 700/500-mb layer, changes radically both in position and intensity, even in the course of 6 to 12 hours —Figs. 1(a) to 1(g). Consequently, very little, if any, quasi-conservatism can be attributed to the partial patterns. Moreover, in view of the observed apparent erratic movement of these thermal systems, it becomes difficult to associate systematic advection of cold or warm air, as the case may be, or transport of the thickness lines with these patterns.

(*b*) While the movement of these thermal systems appears erratic and unpredictable there appears to be two predominant types of partial cold thermal systems over the region—one to the west or northwest, shifting in some easterly direction—Figs. 1(e) to 1(i)—and the other to the east or northeast, shifting in a westerly or southwesterly direction - Figs. 1 (a) to 1 (d) and 1 (j) to 1 (m).

(*c*) The thermal systems do not appear to have any direct correlation with the subsequent occurrence of thunderstorms over the respective areas during a period of 24 hours or more, as can generally be seen from Figs. 1 and 2 and particularly from Figs. 1(l) and 1(o) and Figs. 2 (f, g, h).

(*B*) *Thermal patterns based on data for May 1953*—In order to check the conclusions drawn above, the charts of total and partial thickness patterns for May 1953 have been prepared, making full use of the close network of available pilot balloon winds. The 500-mb pressure contours, together with the total thicknesses (1000/500 mb) and the 'thermal winds' and the charts showing the partial thicknesses (700/500 mb) and the corresponding 'thermal winds' are prepared in the usual manner (Petterssen and Priestley) for all the days from 1 to 8 May 1953, using the 2030 IST radiosonde data and the 1430 IST pilot balloon winds given in the *Indian Daily Weather Reports*.

As the 500-mb surface was generally above 19,000 ft above mean sea level, the actual winds at 20,000 ft which formed the nearest standard level at which the wind was reported and the vertical shear between 2000 and 20,000 ft winds, computed as vector difference were plotted on the 500-mb charts given in Fig. 5. The vertical shear between 10,000 and 20,000 ft winds was plotted on the partial thickness charts given in Fig. 6. Whenever 20,000 ft winds were absent, the winds at 18,000 ft if available, were utilised; such cases are indicated by placing '18' beside such winds. If either the 18,000 ft winds or 20,000 ft winds at 1430 IST were not available for the radiosonde stations, the radar winds at 20,000 ft at 2030 IST, if any, reported by them were used mainly as a qualitative guide for fixing the patterns; such winds are designated by placing 'R' near them on the charts. Furthermore, in drawing the isopleths in Figs. 5 and 6 synoptic smoothing of the radiosonde data has been done, whenever justified consistent with the principle of continuity. The gradients of the thicknesses observed on a few occasions in April 1944 suggest too strong thermal winds, which are out of all proportion with the normal flow patterns over the region. It would, therefore, appear that a quantitative geostrophic spacing of the thickness as well as the contour lines so as to account for the thermal and the actual winds respectively may not always be feasible. However, as the gradients in a large number of occasions in April 1944 were in conformity with the speeds of the normal winds, geostrophic spacing of the contours as well as the thicknesses in Figs. 5 and 6 so as to make them conform to the observed speeds of the actual winds and the vertical wind shear respectively, has been adhered to as far as practicable. The unavoidable disparity between the times of the radiosonde data at 2030 IST and those of the upper winds at 1430 IST, which are principally used in the analysis of the isobaric charts and thickness patterns, has been ignored for the purpose of this study. A critical examination of the theoretical justification for the much needed geostrophic spacing of the lines and the correspondence of the vertical wind shear with the actual 'thermal winds' as presumed in the

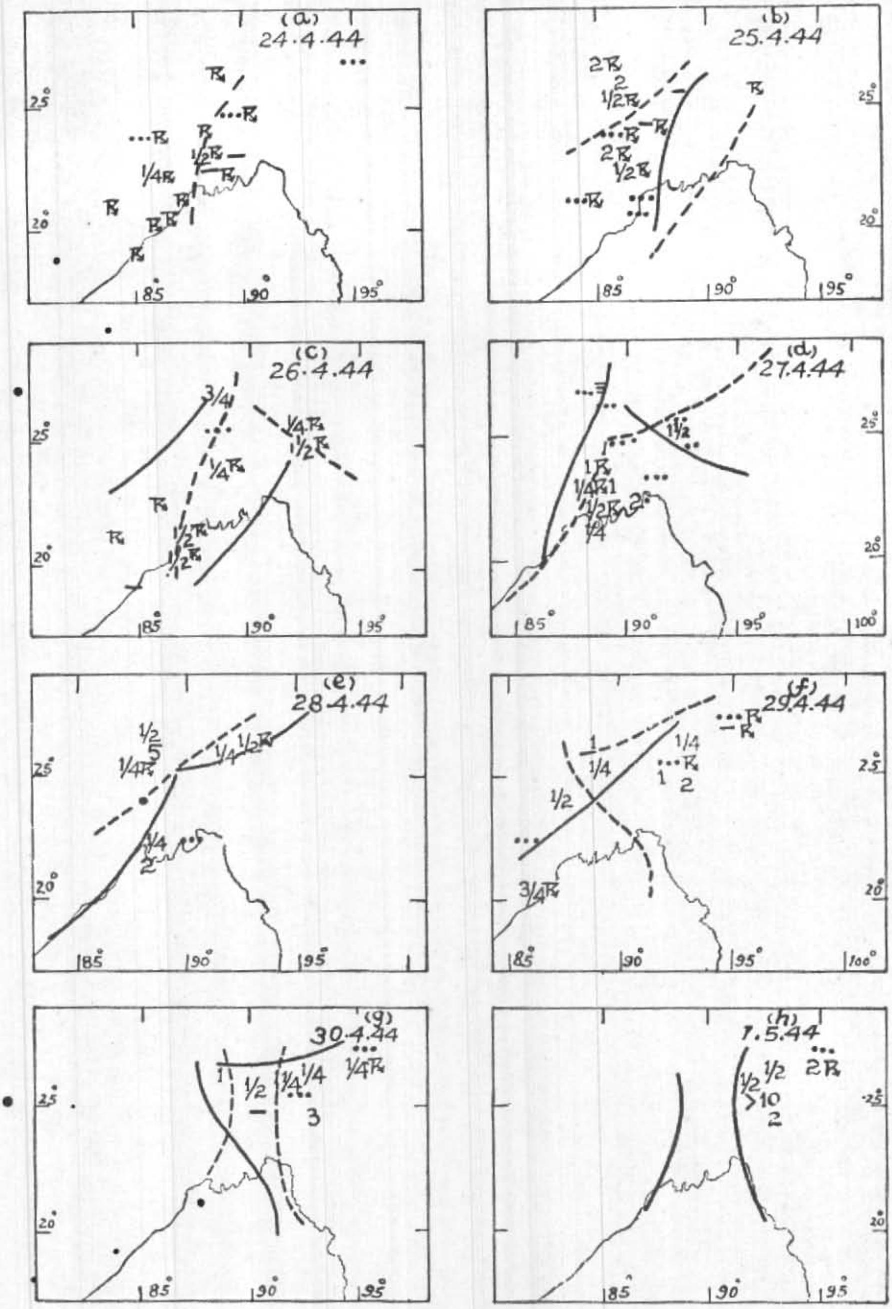


Fig. 2. Actual weather development over the region for periods of 24 hours ending 0830 IST of each day during the period 24 April to 1 May 1944

(The axes of the troughs in the partial thickness patterns seen 36 and 12 hours before 0830 IST of each day are marked in full and dotted lines respectively)

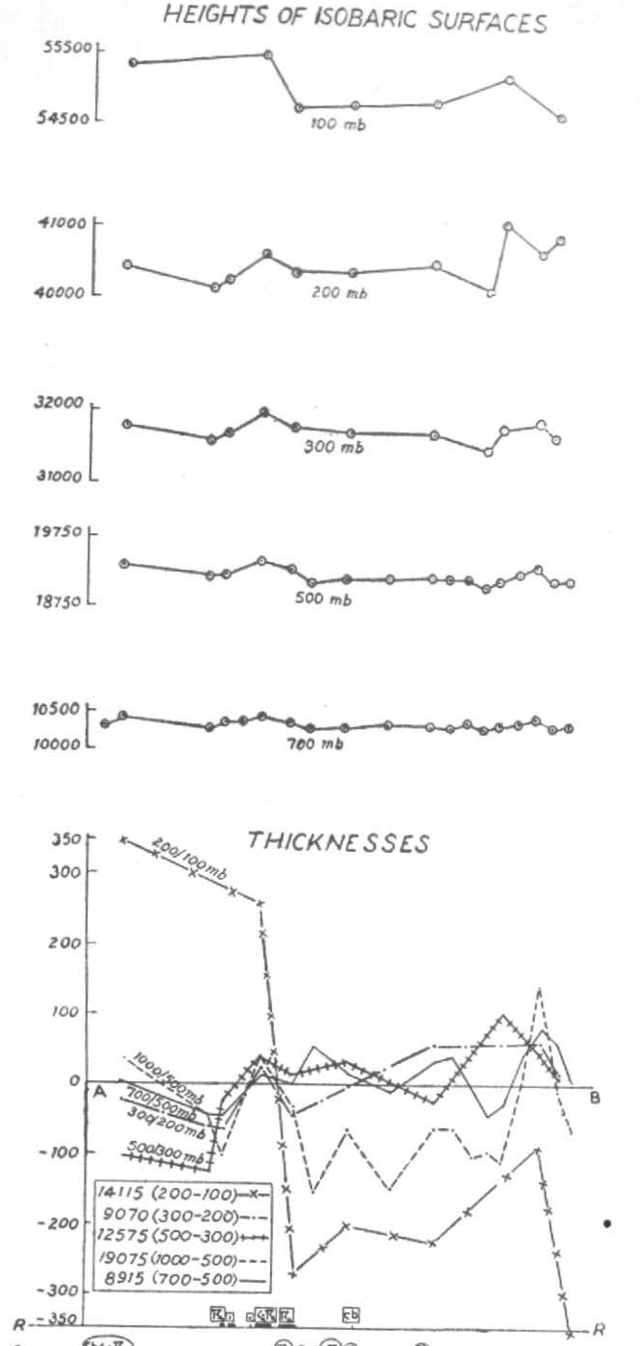


Fig. 3. Variations of the heights of the standard isobaric surfaces and the thickness between them in feet for the period 23 to 29 April 1944 for Calcutta

(The values of the datum line AB for the different sets of thicknesses are also shown)

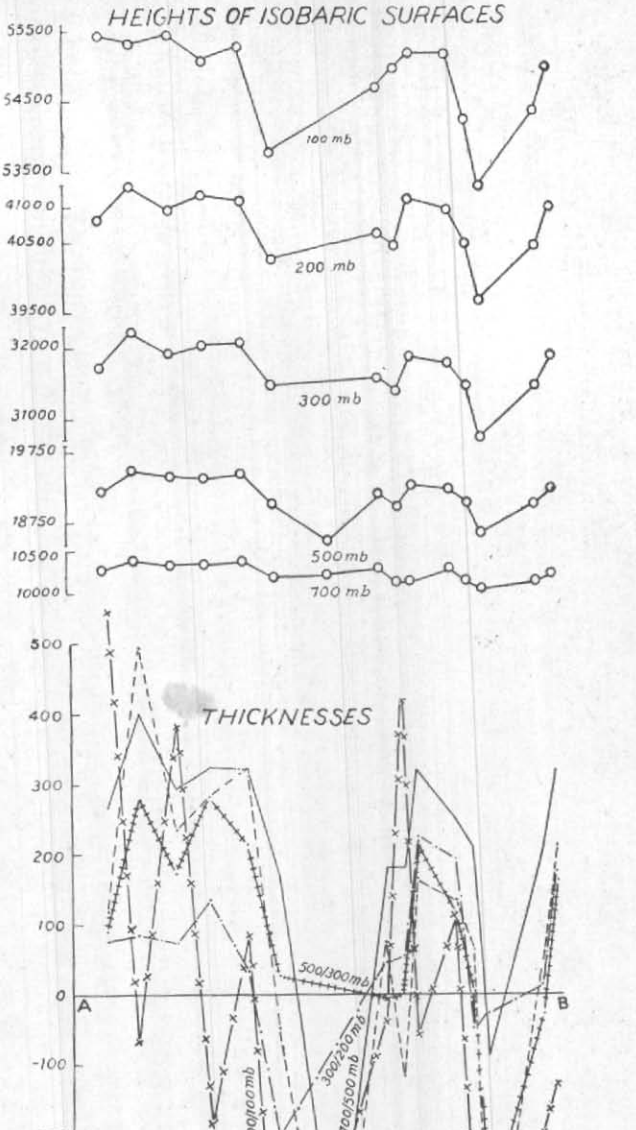


Fig. 4. Variations of the heights of the standard isobaric surfaces and the thickness between them in feet for the period 23 to 29 April 1944 for Bogra

(The values of the datum line AB for the different sets of thicknesses are also shown)

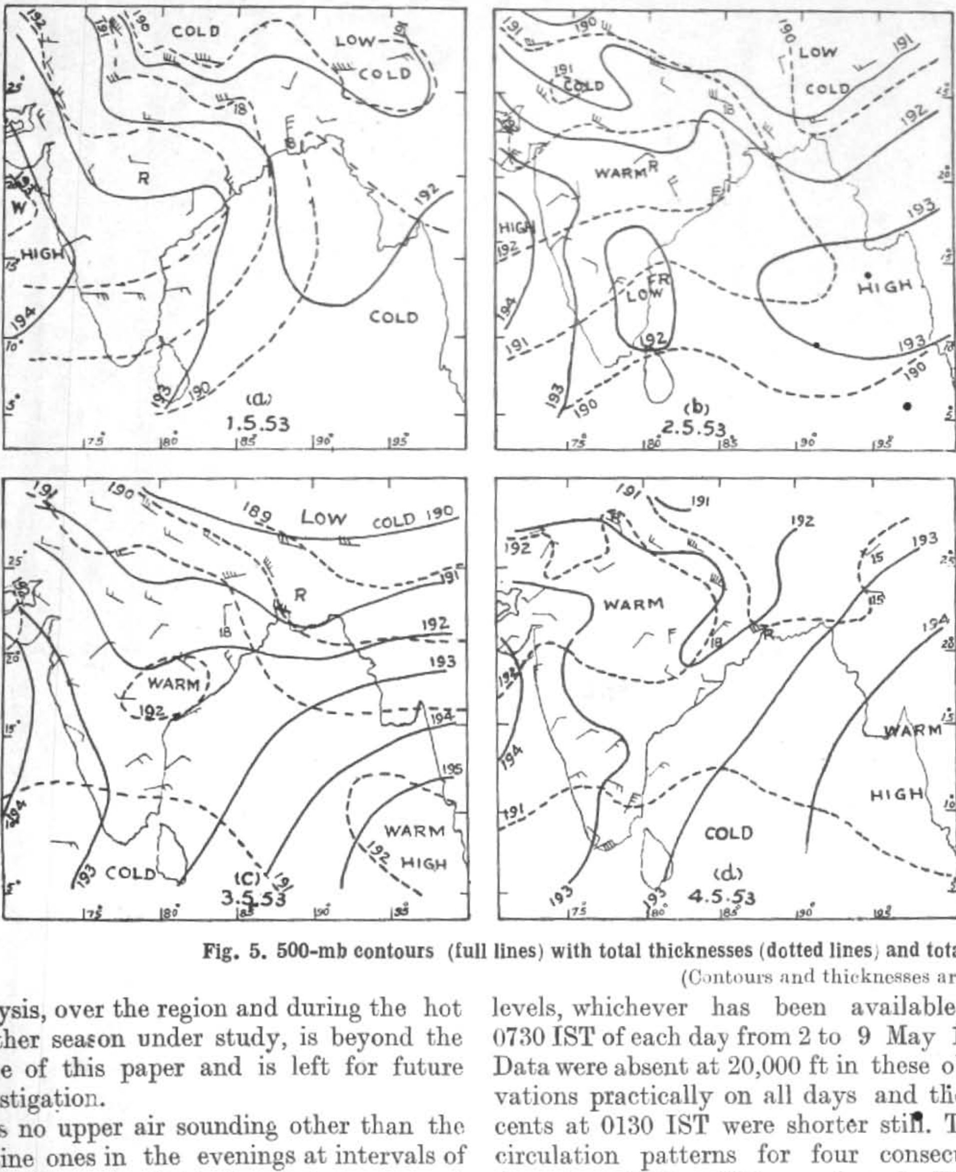
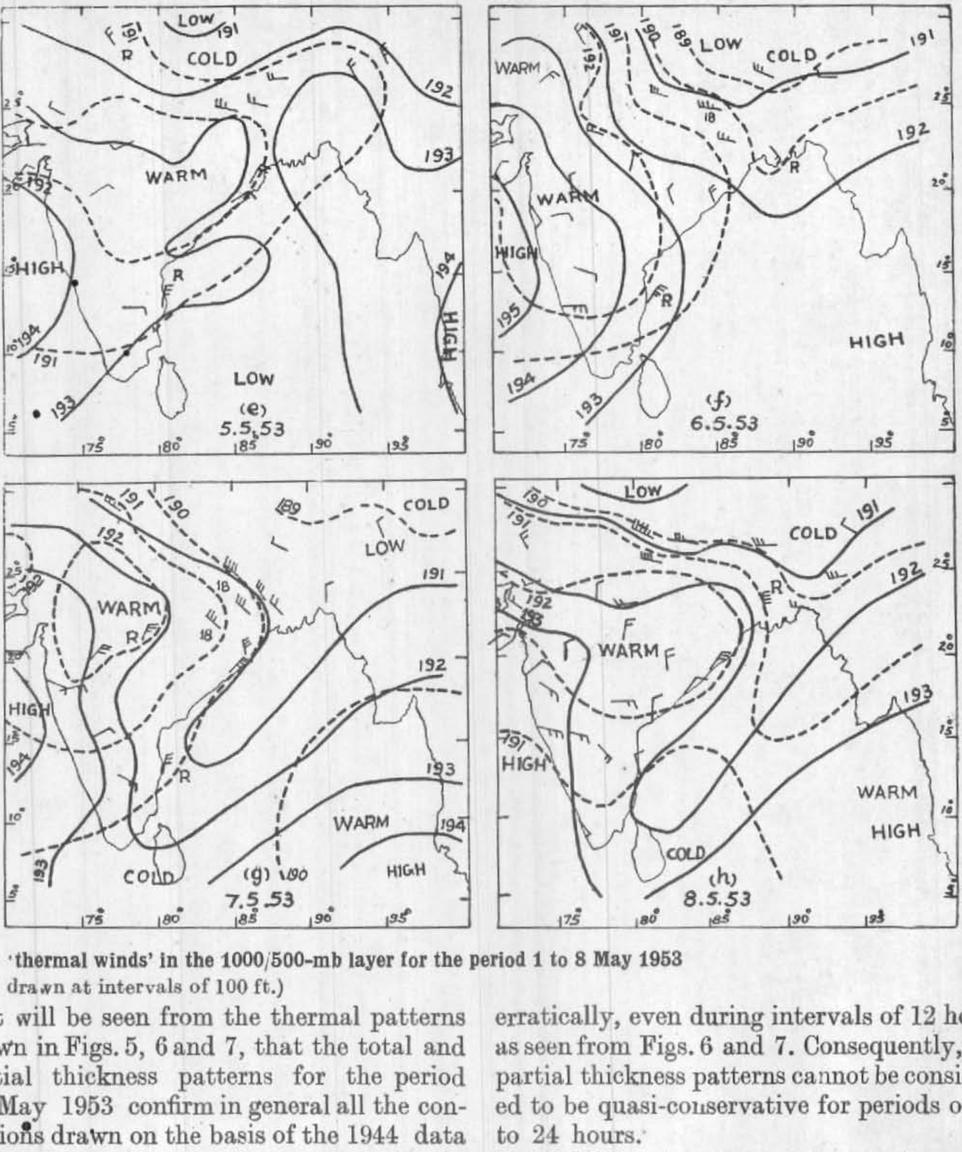


Fig. 5. 500-mb contours (full lines) with total thicknesses (dotted lines) and total
(Contours and thicknesses are

analysis, over the region and during the hot weather season under study, is beyond the scope of this paper and is left for future investigation.

As no upper air sounding other than the routine ones in the evenings at intervals of 24 hours was available for stations, except for Calcutta itself, in and near the region under consideration, it has not been possible to examine the behaviour of the thickness patterns at smaller intervals of time than 24 hours during the period in May 1953. However, this aspect of the partial thickness patterns has been qualitatively studied by preparing charts showing the relative circulation patterns of the vertical wind shear between 10,000 ft and 18,000 or 15,000 ft levels, whichever has been available, at 0730 IST of each day from 2 to 9 May 1953. Data were absent at 20,000 ft in these observations practically on all days and the ascents at 0130 IST were shorter still. These circulation patterns for four consecutive days from 2 May 1953 are given in Fig. 7. Although they are subject to the inevitable limitation of being not fully representative of the vertical shear within the 10,000 and 20,000-ft levels, corresponding to the thickness patterns within the 700/500-mb layer, it is felt that they will show, though qualitatively, the probable configuration of the partial thermal systems observed on a particular evening towards the morning of the succeeding day.



'thermal winds' in the 1000/500-mb layer for the period 1 to 8 May 1953
drawn at intervals of 100 ft.)

It will be seen from the thermal patterns shown in Figs. 5, 6 and 7, that the total and partial thickness patterns for the period 1-8 May 1953 confirm in general all the conclusions drawn on the basis of the 1944 data except that as these patterns refer only to intervals of 24 hours, the marked changes in the thermal systems during smaller intervals of time, which are evident from the 1944 patterns, are not very apparent from them. Nevertheless, it is seen from these figures, that while the total thickness patterns are more or less semi-permanent from day to day, the partial thickness patterns appear to vary both in intensity and position quite erratically, even during intervals of 12 hours as seen from Figs. 6 and 7. Consequently, the partial thickness patterns cannot be considered to be quasi-conservative for periods of 12 to 24 hours.

(*C*) *Thermal systems and actual weather development*—The actual development of weather over the region under study during 24-hour periods ending 0830 IST of each day for the periods 24 April to 1 May 1944 and 2 to 9 May 1953 is shown in Figs. 2 and 8 respectively*. The axes of the partial cold thermal systems within the 700/500-mb layer shown in Figs. 1 and 6 are marked on these diagrams in the following manner: those for

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*The weather developments shown in Figs. 2 and 8 refer *chiefly* to those which have occurred since the previous afternoon and/or evening

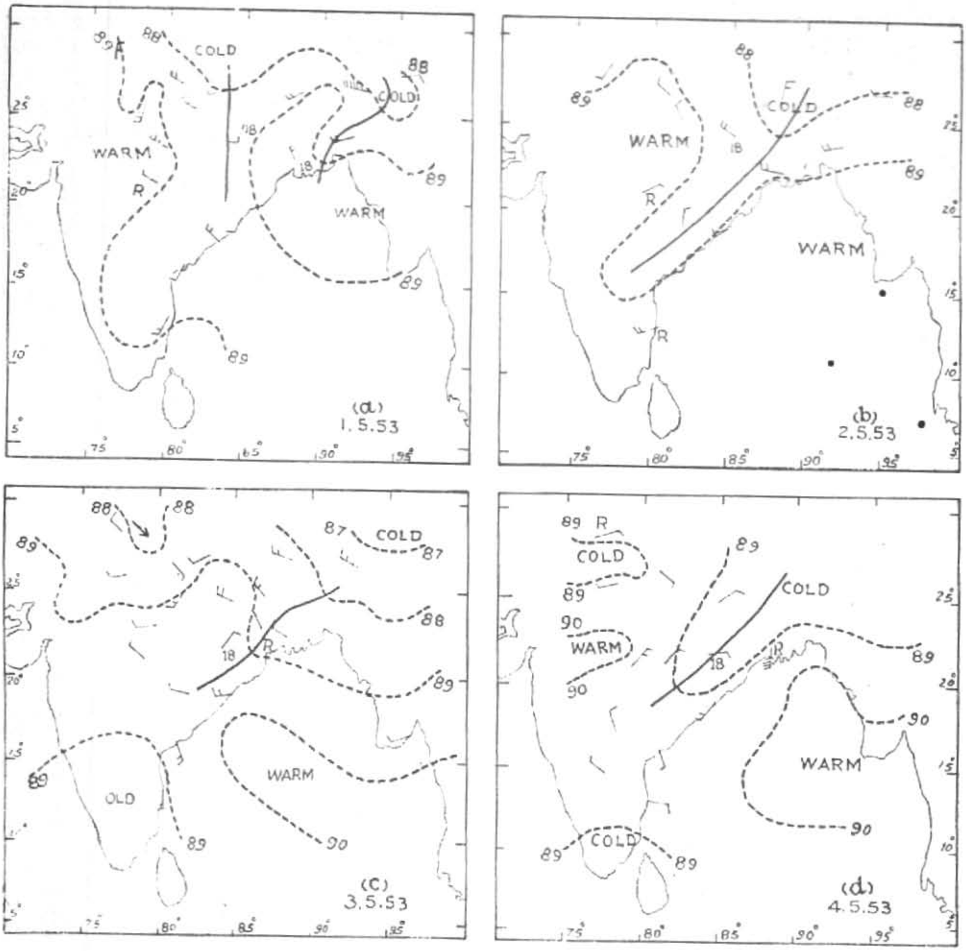
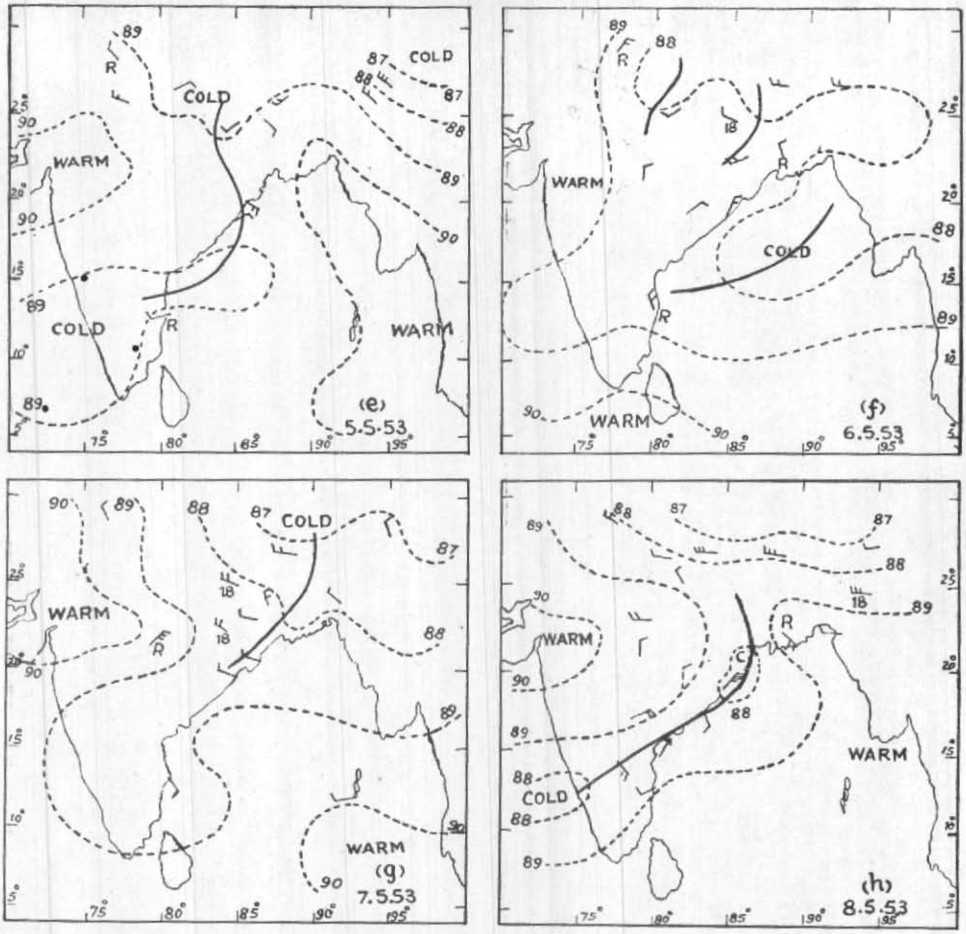


Fig. 6. Partial thickness patterns and 'thermal winds' in
(Thickness lines are drawn at intervals of

the evening of the 1st are marked in full lines and those for the evening of the 2nd are marked in dotted lines respectively on the chart containing the weather remarks for the 24-hour period ending 0830 IST of the 3rd; and similarly for the other days. This is done with a view to examine if any correlation existed between the position of the cold thermal systems and the subsequent development of weather recorded a little over 24 hours or 12 hours respectively later.

It will be seen from Figs. 2 and 8, that the actual development of weather during a period of 24 hours or more showed no cognisable correspondence with either the earlier location or the intensity of the cold thermal systems (Figs. 1 and 6), whose axes are shown in full lines. The troughs seen on the evenings of 23, 24, 26 and 29 April 1944 and 2 and 4 May 1953 are particularly striking in this respect. In spite of the fact, that the trough was associated with a southerly 'thermal wind' of about 35 knots at Calcutta at 2030 IST of 4 May 1953 (Fig. 6-d) no thunderstorm occurred over Calcutta stations upto 0830 IST of the 6th although active nor'westers developed at the stations in the afternoon/evening of 4th itself (Table 1). The so-called 'inhibiting effect' of a warm ridge observed on a particular day against the development of thunderstorms 12 to 36 hours later, is also not much in evidence, as can be seen from a comparison of the thermal systems for



the 700/500-mb layer for the period 1 to 8 May 1953
100 ft. The axes of the troughs are shown by full lines)

5 and 6 May 1953—Figs. 6(e) and 6 (f), showing a warm high over East Pakistan and Lower Assam, with the actual weather development during the 24 hours ending 0830 IST of the 7th and 8th respectively—Figs. 8(f) and 8(g), indicating a dense crop of thunderstorms over the same areas. The above findings are true of the total thickness patterns as well.

On the other hand, the partial thickness patterns seen on a particular evening seem to influence the development of thunderstorm during the same evening and night. This fact is evident from the partial thickness patterns, whose axes are drawn in dotted lines for 24, 25, 26 and 28 April 1944 (Fig. 2) and 2, 4, 6, 7 and 8 May 1953 (Fig. 8) and the actual weather development over the region upto 0830 IST of the succeeding days. Considering the apparently erratic movement of thermal troughs on the partial thickness charts, as revealed by the examination of April 1944 and May 1953 data, it is felt that, while the development of an active *Cb* cell to the stage of a full-grown nor'wester cloud may, to a large measure, be helped by the existence at the time of a cold pool of air in the 700-500 mb layer, it is futile to expect that we should be able, as a rule, to forecast the thundersquall activity over a given small area with reference to any particular sector of the thermal system, which is noticed some 24 to 36 hours earlier. Further, the fact that the nor'wester thunderstorms occur mostly in the afternoon and evening, *i.e.*, near about the

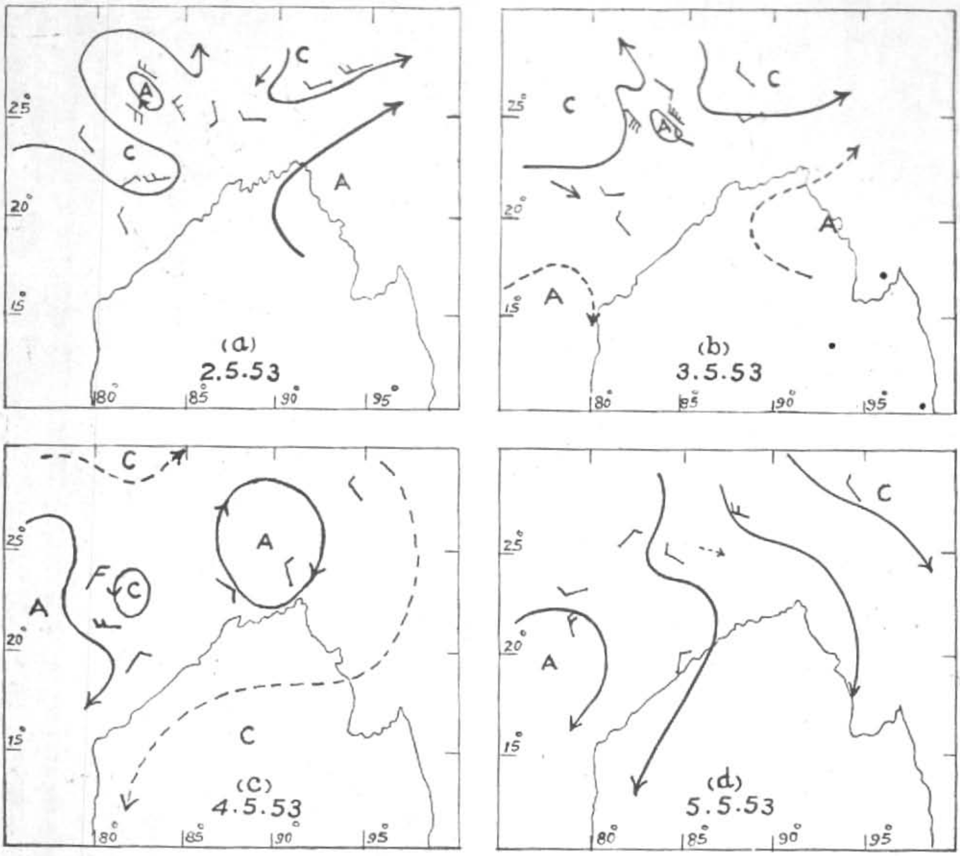


Fig. 7. Relative circulation patterns of vertical wind shear between 10,000 ft and 18,000 or 15,000 ft at 0730 IST for the period 2 to 5 May 1953

epoch of maximum ground heating, indicates unmistakably that they are chiefly caused by the moisture and thermal conditions in the lower layers of the troposphere, rather than by the movement of the cold troughs or pools aloft, although the coincidence of the upper level cold thermal system with the above-mentioned favourable conditions in the lower layer may be a contributory factor for the development of the thunderstorms.

The foregoing discussion in this section tends to show, that while the partial thickness patterns of the previous day have no medium-range prognostic value for forecasting the nor'westers, they seem to influence the development of the thunderstorms on the same day soon after the appearance of the thermal systems, as one would, indeed, expect from thermodynamical considerations.

(*D*) *Partial thicknesses and thermal instability*

(*i*) In order to see how far the thicknesses in the mid and upper troposphere suggest progressive 'advection' of cold air at intervals shorter than 24 hours, leading to the development of thunderstorms at individual stations, or *vice versa*, diagrams illustrating the progressive variations of the actual thicknesses, as well as the heights of the various standard isobaric surfaces observed at Calcutta and Bogra during the period in April 1944 are drawn—Figs. 3 and 4 (pp. 14-15). The daily sequence of weather at the two stations is marked in symbols at the appropriate hours on the time axis PP on the respective

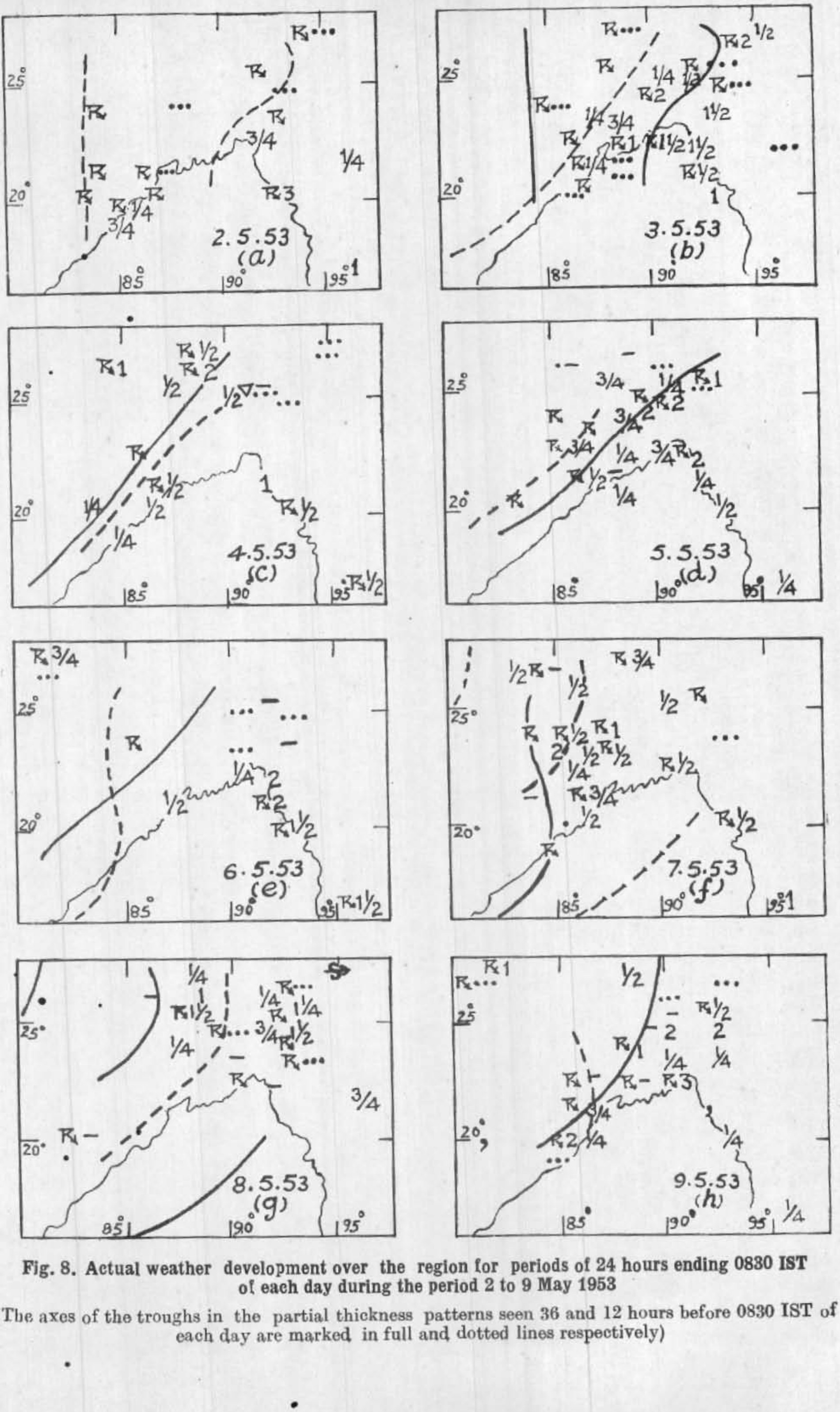


Fig. 8. Actual weather development over the region for periods of 24 hours ending 0830 IST of each day during the period 2 to 9 May 1953

(The axes of the troughs in the partial thickness patterns seen 36 and 12 hours before 0830 IST of each day are marked in full and dotted lines respectively) diagrams. The thick lines on the time axis indicate the duration of the occurrence of weather shown by these symbols. The symbols shown in circles and squares on the time axes marked QQ and RR represent the sequence of the above weather developments advanced by 12 and 36 hours respectively. The latter are marked in order to see if the observed thickness variation at a particular time had any relation to the weather that occurred at the station 12 or 36 hours respectively later.

These diagrams show the following two features—

(*a*) The variations of the heights of the isobaric surfaces are generally in phase even upto the 100-mb level, almost on all the days. This suggests that the type of advection, if any, between the various isobaric surfaces is sensibly the same upto the 100-mb level; while aloft, the nature of advection may be different. Accordingly, the presence of a cold pool or trough within the 700-500 mb layer, and for that matter within any other layer below 100-mb surface, on a particular day compared to a previous occasion, will mean the existence of a corresponding cold pool or trough aloft and hence, it need not necessarily indicate thermal instability on the day in question.

(*b*) The actual thicknesses vary erratically, suggesting advection of cold or warm air, if any, at intervals smaller than 24 hours (Figs. 3 and 4). Also, their variation does not show any correlation with the weather development as much in advance as 36 or even 12 hours prior to the occurrence of thunderstorms.

(*ii*) As an analysis of the actual thicknesses at shorter intervals, as done above for the period in 1944 under review, is not possible in 1953, for lack of observations, the thermal instability likely to be induced by the partial thermal systems and its utility or otherwise for forecasting nor'westers at an individual station is dealt with, with reference to Calcutta (Dum Dum), which alone has an upper air sounding at 0830 IST prior to the outbreak of thunderstorms in the afternoon or evening, and 12 hours after the thermal systems have been noticed at 2030 IST of the previous day. For this purpose, it is *assumed* that the partial thicknesses are 'quasi-conservative' and that the coldest portion of the thermal trough or pool, corresponding to the lowest thickness line of the partial thickness pattern in the region, within a distance of 200 to 800 miles from Calcutta, will be transported over the station and consequently, the temperature within the 700/500-mb isobaric layer over the station at 0830 IST of the next day will be altered to the values corresponding to those indicated by the lowest thickness value. This change in the temperature distribution within the 700/500-mb isobaric layer, which is the *maximum* possible owing to the transport over the station of the so-called 'conservative' thickness line, is also assumed to occur near the time of occurrence of thunderstorms in the afternoon or evening. The results of such analysis made for Calcutta (Dum Dum) for all the days from 1 to 9 May 1953 are given in Table 2.

Temperature (°C) given in columns 3 and 4 of this table are those corresponding to the lowest thickness values given in col. 2 (see Fig. 6); and are computed from the table given in Petterssen and Priestley's memorandum (V.T.M. No. 2); while those in col. 5 are the temperatures at the 700-mb level obtained by assuming the lowest thicknesses and the observed lapse rate (nearly saturation adiabatic value) indicated by the evening soundings. The temperatures in cols. 6, 7 and 8 are the actual temperatures picked out from the 0830 IST ascent curves. The thermal changes likely to be caused in the 700/500-mb layer consequent on the transport of the lowest thickness line over the station are given in cols. 9, 10 and 11.

Temperature changes in cols. 10 and 11 indicate a cooling at the 700-mb level on all the days, while a rise, instead of a fall of temperature on the 5th, 6th and 7th is indicated at the 500-mb level. The rise of temperature at the 500-mb level, it may be argued, is owing to the circumstance that the temperature at 0830 IST at this level, is already lower than what is likely to be the result of the transport of the lowest thickness; and may

TABLE 2

Temperature (°C) variations within the 700/500-mb layer over Calcutta (Dum Dum)

	On the evening of				On the morning of				Change of temperature due to transport of lowest thickness line		
Date	Lowest thickness line near Calcutta (*ft*)	Mean virtual temperature $\gamma=0$	Computed temperature at 500-mb level $\gamma=8$	Computed temperature at 700-mb level $\gamma=8$	Actual mean virtual temperature	Actual temperature at 500-mb level	Actual temperature at 700-mb level	Mean virtual temperature	Temperature at 500-mb level	Temperature at 700-mb level	Weather
1-5-53	8800	−3	−10	3	..	..	..	..	..	..	..
2-5-53	8800	−3	−10	3	−1	−8·5	8·5	−2·0	−1·5	−5·5	Thunderstorm with squall 62 mph
3-5-53	8900	1	−6	8	4	−3·0	13·0	−7·0	−7·0	−10·0	..
4-5-53	8900	1	−6	8	4	−1·0	11·0	−3·0	−5·0	−3·0	Thunderstorm with squall 53 mph
5-5-53	8900	1	−6	8	3	−7·0	12·0	−2·0	1·0	−4·0	Lightning
6-5-53	8800	−3	−10	3	1	−8·5	10·0	0·0	2·5	−2·0	Thunderstorm with squall 64 mph
7-5-53	8800	−3	−10	3	−2	−11·0	7·0	−1·0	1·0	−4·0	..
8-5-53	8800	−3	−10	3	2	−3·0	12·0	−5·0	−7·0	−9·0	Squall 37 mph
9-5-53	..	..	..	..	6	0·0	13·0	−9·0	−10·0	−10·0	Thunderstorm with squall 86 mph

tempt one to presume that further cooling by 'advection' of cold air within the layer may proceed with progress of time. Such a presumption is obviously ill-founded for the reason, that it tends to question the 'quasi-conservatism' of the thicknesses; besides, it does not take into account the equal probability of 'warm air advection' at this level over the station since the 0830 IST ascent. Taking for granted, therefore, the thermal changes given in cols. 10 and 11 to be consistent with the 'quasi-conservatism' of the thicknesses, a paradox becomes evident when the changes in the conditions of thermal instability caused by them are compared with the actual weather development over the station given in Table 1 and reproduced in col. 12 of Table 2.

In order to show the resultant change in instability, in terms of available energy arising out of the transport of the coldest portion of the partial thermal system within the 700/500-mb layer over Calcutta, the ascent curves based on the 0830 IST soundings for 3 and 6 May 1953 and their modifications owing to the transport of the lowest partial thickness of the previous day are shown in Fig. 9. A striking feature of Fig. 9 on comparison with the local weather development is, that even though the increase in instability in accordance with the assumed transport of the lowest thickness was very large on the 3rd, there was no thundery activity or a squall over Calcutta on this day; while on the 6th, when a slight cooling at the 700-mb level and a warming at the

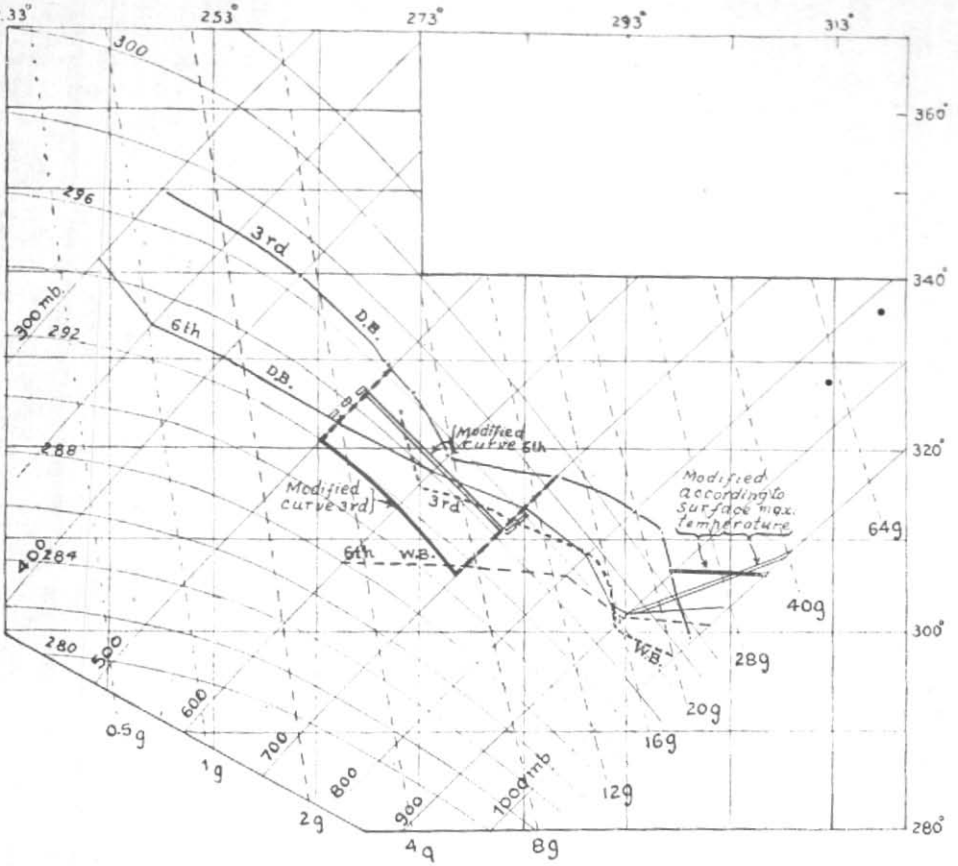


Fig. 9. Upper air soundings of Dum Dum at 0830 IST of 3 and 6 May 1953

(DB in full lines and WB in pecked lines. Modifications of the environmental curve (DB) by the assumed transport of the lowest thickness line and the surface maximum temperature on these days are shown by thick and double lines respectively)

500-mb level, resulting in a decrease of instability and available energy were indicated, the station experienced a severe nor'wester with a surface squall of 64 mph. It may be mentioned here, that the moisture content in the lower layers of the atmosphere over the station was only slightly higher on the 6th compared to the 3rd. Furthermore, if the development of the nor'wester is assumed to be induced mainly as a result of the 'overturning' caused by the transport of the cold pool or trough in the 700/500-mb layer and that the downdraft of the potentially colder air causes the ground squall, the modified air at the 700-mb level on the 6th, being potentially the coldest, should have descended to the ground in order to give rise to the observed surface cooling and squall. It will, however, be seen from Fig. 9, that, without taking into account entrainment processes, this modified parcel at the 700-mb level on the 6th could sink hardly below 750-mb level; while on the 3rd, it could descend even upto the 850-mb level. And yet, there was nor'wester and squall on the 6th and none on the 3rd. The paradox between the change in instability caused by the assumed transport of the cold thermal system and the actual weather at the station, on these two representative days, becomes all the more striking, if the lower portions of the ascent curves below the 700-mb level are also modified in accordance with the day's maximum temperature at the surface level (Fig. 9).

It is to be noted, that there are obviously many restrictions in adopting the above procedure for estimating the change in instability consequent on the thermal changes in the 700/500-mb layer by the transport of the earlier cold thermal system on the day when thunderstorms are expected to occur over the station. The apparent erratic movement of the partial thickness patterns, as already mentioned earlier, does not, in the first instance, lend any support for assuming systematic transport of the thermal system. Secondly, the actual thickness values observed over the station, day by day, do not even remotely suggest the possibility of such a progressive change in the thermal structure of the isobaric layer (Fig. 6), as also borne out by the actual variation of the partial thicknesses at shorter intervals of time on the basis of the 1944 data (Figs. 3 and 4). Further, changes of temperature above and below the 700/500-mb isobaric layer have not been considered for the purpose of the above assessment of thermal instability.

Notwithstanding the above-mentioned limitations, the above analysis brings out conspicuously the maximum change in the thermal instability characteristics owing to the transport over a station of the lowest thickness observed in its neighbourhood on the previous day and the unreliability as well as the inefficacy of the partial thickness patterns alone to produce thermal instability resulting in nor'westers. It also draws pointed attention to the risk of failure involved in forecasting the nor'westers, especially at individual stations, on the basis of the partial thickness patterns noticed earlier.

Similar analysis in respect of the total thicknesses has not been attempted, on account of the observed semi-permanence of these patterns on days of nor'westers and of no nor'westers.

3. Dynamics of the thermal system and the resulting development patterns

With a view to see whether the thermal divergence depending on the thermal vorticity at the 500-mb level and the resulting cyclogenetic field has had any effect on the occurrence of thunderstorms, the 'development' after Sutcliffe (1947, 1950), over the northeast India and East Pakistan region is computed from the 500-mb charts (Fig. 5) for all the days, using the method given by Sawyer and Matthewman (1951). The relative* development patterns based on computations at a close network of points are reproduced in Fig. 10. Isopleths of positive development (marked C) are drawn in full lines and those of negative development (marked D) are drawn in dotted lines in units of 10^{-2} hr^{-2}. Taking into account the field of development and the times of commencement of the thunderstorms at the various stations in northeast India, as reported in their *Monthly Meteorological Registers*, arrows are marked on these diagrams indicating the places of first outbreak of the thunderstorms and the probable course followed by them.

These development patterns at 2030 IST† of each day (Fig. 10) bring out the following salient points, on comparison with the weather charts in Fig. 8 —

(*a*) Greater density and intensity of weather development appear more or less to coincide with the regions of the recent positive development, except over sub-montane regions, where orography seems to have decidedly influenced the weather development, in spite of the observed fields of negative development over these regions.

(*b*) Weather, which has occurred over other regions of negative development, may perhaps be attributed either to the travel of the earlier thunderstorms initiated over the neighbouring areas of positive development and/or high grounds, as indicated in most cases by the arrows marked on the

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*The values of development as computed are only relative, though they are quantitative, in so far as the correction for variation of gravity and coriolis parameter from Lat. 50° to those at Lat. 20° for which the grid scale has been used, has not been applied to them

†Though the 500-mb surface refers to 2030 IST radiosonde data, the patterns of development may also be considered to refer more to 1430 IST than to 2030 IST, as the winds used to fix the geometry of the contours as well as the thicknesses refer to 1430 IST

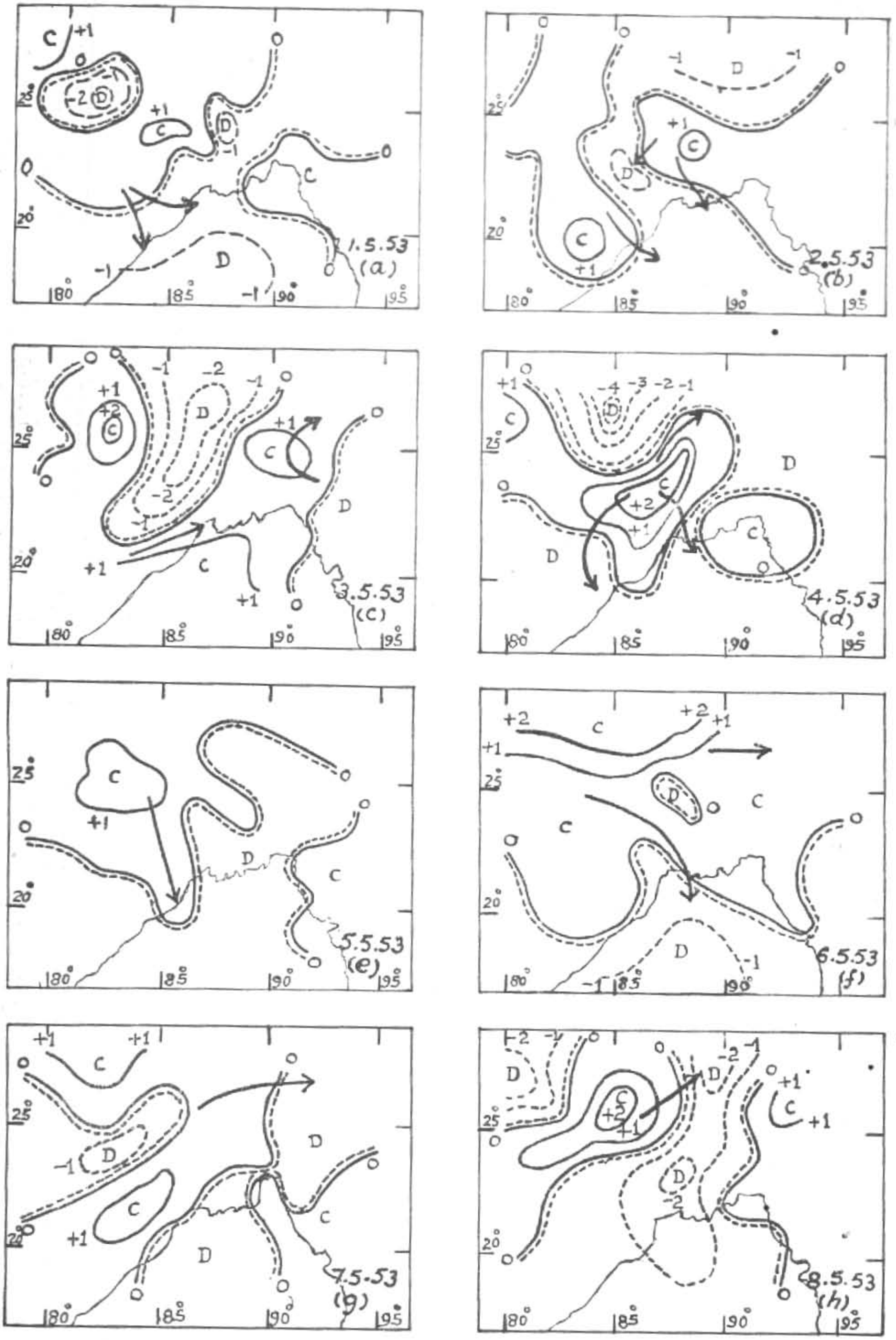

Fig. 10. Development patterns for each day of the period 1 to 8 May 1953

(Full lines indicate positive development and dotted lines negative development, in units of 10^{-2} hr $^{-2}$)

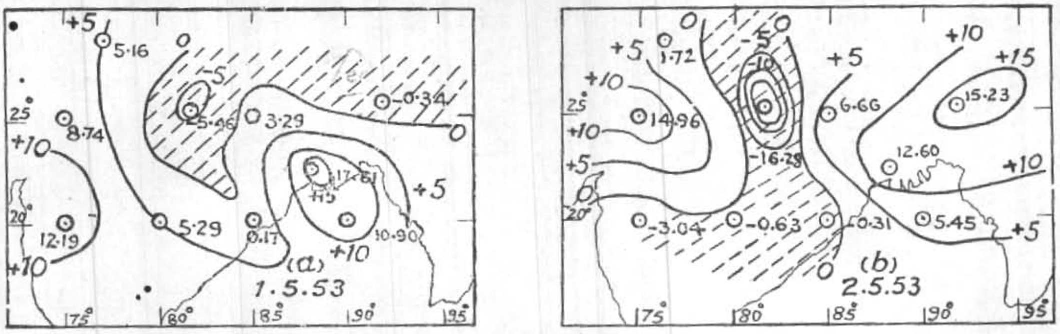

Fig. 11. Patterns of vertical component of absolute vorticity of geostrophic winds on 1 and 2 May 1953
(Areas of negative vorticity are shown by hatching. Unit : 10^{-5} sec^{-1})

diagrams; or to the variation of the patterns of development from an anti-cyclogenetic (negative values) into a cyclogenetic field (positive values) over these areas.

(c) Some promise of a prognostic value of these patterns for the purpose of forecasting the development of the 'seasonal' weather over the regions, however, seems possible on days when a moving 'low' such as a western disturbance or a low pressure wave characterise the synoptic situation affecting the region. The patterns for 5 May 1953—Fig. 10(c)—and the corresponding weather developments until the morning of the 7th shown in Fig. 8 (f), following a well-marked cyclonic circulation upto the 7000-ft level observed over Chota Nagpur and neighbourhood on the 6th morning, perhaps, lend some support to this view.

It will be seen, therefore, that except for the association of the immediate occurrence of weather and perhaps on days, when moving pressure systems control the weather development over the region, very little prognostic value can be assigned to the thickness patterns for forecasting such small-scale and short-lived instability phenomena as the thunderstorms, considering the above-mentioned relation between the actual occurrence of weather and the 'development' patterns, which represent the dynamical aspect of the thickness patterns.

4. Vertical component of absolute vorticity of geostrophic winds

Charts of vertical component of absolute vorticity of the *geostrophic* winds* computed from the 500-mb contours (Fig. 5) using a relation due to Cressman (1953), have been prepared on all the days from 1 to 8 May 1953, in order to see whether progressive and systematic variation of vorticity, if any, may lead to the development of nor'westers, so as to consider it as a useful prognostic factor for forecasting the occurrence of thunderstorms over the different areas or stations sufficiently in advance. The results of this analysis have not been encouraging in this respect, as illustrated by the patterns of vorticity for two consecutive days (1 and 2 May) given in Fig. 11. During this period, thunderstorms occurred at Calcutta on the 2nd, while no thunderstorm occurred on 1 and 3 May 1953. The vorticity observed over Calcutta on 1 and 2 May, however, did not throw any useful light for predicting the above variation of weather at the station; nor were the patterns of vorticity helpful for predicting the thunderstorms over wider areas. It is, however, interesting to note that the patterns of vorticity given in Fig. 11 and similarly for the remaining days (not reproduced here) are more or less in qualitative agreement with the patterns of 'development' for the corresponding days given in Fig. 10.

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*As the correction factor for determining the vorticity of the *actual* winds could not be calculated owing to the paucity of wind data, the vorticity of the actual winds could not be derived from that for the geostrophic winds computed from the isobaric surface

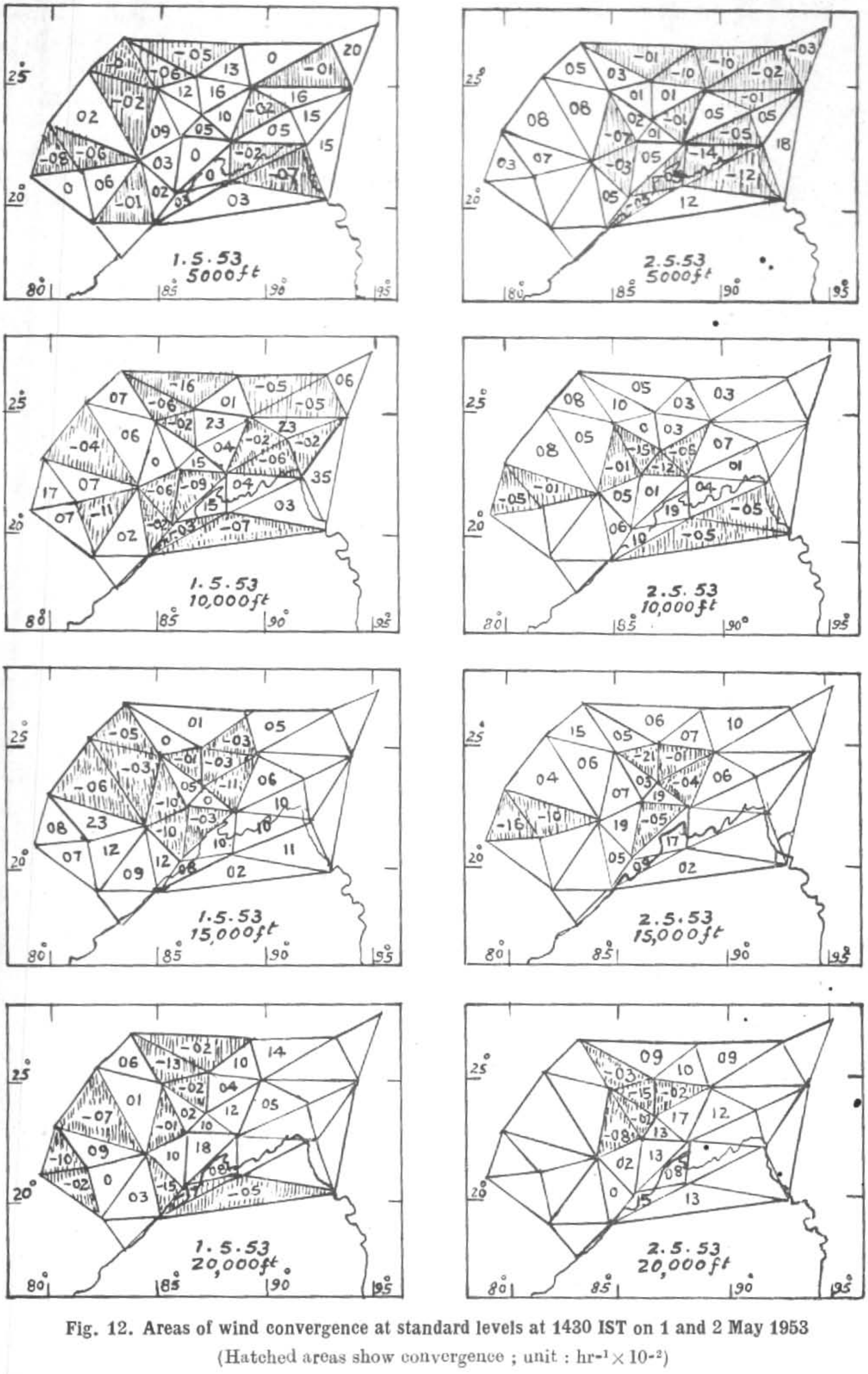

Fig. 12. Areas of wind convergence at standard levels at 1430 IST on 1 and 2 May 1953

(Hatched areas show convergence ; unit : $hr^{-1} \times 10^{-2}$)

5. Computation of wind velocity convergence

The seasonal heat low at the surface and the associated convergence in the surface layers of the atmosphere, sufficient insolational trigger derived from ground heating during the afternoon as well as latent instability are almost normal features of the atmosphere over northeast India during nor'wester situations. Nevertheless, it is an observed fact, that thunderstorms do not occur at one and the same station or area on every such occasion. It was, therefore, felt that the wind velocity convergence and its progressive increase at some suitable higher level or levels rather than at the surface layers, might supplement the daily available insolational trigger, in order to release the latent instability culminating in the development of nor'westers; and that the field of convergence at the higher level or levels might provide a useful guide for forecasting the thunderstorms. Accordingly, charts of wind convergence at 5000, 10,000, 15,000 and 20,000-ft levels over the region under study, have been prepared for all the days during the period 1-8 May 1953, using the available network of pilot balloon winds at 1430 IST. Only a few representative charts for 1 and 2 May, are reproduced in Fig. 12. Hatched triangles indicate regions of convergence. The objective method of Bellamy (1949), instead of the wind component method using isopleths of u and v, has been adopted for this computation, as the former is easily adaptable as a daily forecasting technique, whereas the latter method is more laborious in practice compared to the former.

It is found from this analysis, that the patterns of convergence at the 5000-ft level showed a remarkably good correspondence with the areas, where thunderstorms developed during the same evening and night, while, those at any of the higher levels, even at 1430 IST, which was close to the usual time of outbreak of the nor'westers, did not throw any useful light on their usability as a factor for predicting the thunderstorms. A comparison of Fig. 12 with the actual development of weather shown in Fig. 8 (a, b) illustrates this point. The above inference is, however, subject to a reservation imposed by the limitation of lack of sufficient wind data for levels at hand above 10,000 ft over the region as a whole for the period under review. The absence of correspondence of the observed fields of convergence above 5000 ft level with the actual development of thunderstorms is also not surprising, in view of the fact, that they refer to 1430 IST, which itself is much earlier than the time of commencement of thunderstorms at most of the places; and as such, they are not likely to reflect the distortion of the environmental velocity field, which appears with the development of the cumulus cells and increases rapidly thereafter with the growth of the cumulus into cumulonimbus clouds (Byers and Braham 1949).

6. Conclusion

From the point of view of thermodynamics the observed semi-permanence of the total thickness patterns within the 1000/500-mb layer and the large variability and erratic movement of the partial thickness patterns within the 700/500-mb layer, as seen within the limits of errors of the present analytical facilities, do not lend any support, having a sound physical basis, to regard these thickness patterns as reliable prognostic factors for forecasting the nor'westers 12 to 36 hours in advance of their actual occurrence. As far as an individual station is concerned, the variation of actual thicknesses and the changes in thermal instability likely to be caused on the assumption of the transport of the cold thermal system, delineated by the partial thickness patterns in its vicinity on the previous day, are themselves largely unrelated to the actual development of nor'westers over that station, as illustrated in the case of Calcutta and Bogra. For this reason, greater caution is required to be exercised in treating the thermal patterns as reliable guides for forecasting nor'westers or no nor'westers at an individual station than over comparatively larger areas.

The dynamical aspect of the thickness patterns, as deduced from the theory of Sutcliffe, is more applicable to the study of the evolution and prognosis of large scale circulations such as travelling pressure systems, and are apparently not suited for forecasting such small-scale and short-lived instability phenomena as the thunderstorms, except on occasions when a moving pressure system or wave controls the development of the seasonal weather.

Although the thickness as well as the 'development' patterns do not appear to have any significant medium-range prognostic value, for predicting the thunderstorms 12 to 36 hours ahead of their actual occurrence, the presence of the partial thermal systems and the field of development, at and near the time of outbreak of the thunderstorms, appear to influence the density and intensity of actual weather development, which accompanies them almost immediately. This coincidence, having no significant forecasting value is, however, to be regarded as fortuitous, when one considers the unpredictably quick variations of the development patterns observed on normal days uninfluenced by moving pressure systems and of the partial thickness patterns, at short intervals of time.

The difficulty of using the patterns of vorticity and of wind velocity convergence as forecasting factors, becomes apparent in the light of the fact, that for ascribing any prognostic value to them, more data from a closer network of stations and at more frequent intervals of time than at present available are needed. The spatial distribution of the field of vorticity can be assessed accurately, only if the computation is based on the 500-mb contours drawn uniquely, as pointed out by Cressman. This is possible only if more data are available than at present. Similarly, more upper wind data from a closer network of stations at shorter intervals than at present are essential for computing the velocity convergence over smaller areas comparable with the dimensions of the phenomenon under investigation. When such comprehensive data become available, these methods of upper air analysis can, perhaps, be adopted profitably as routine forecasting practices for predicting the nor'westers, sufficiently in advance of their occurrence.

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