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Forecasting of Thunderstorms in Western India in pre-monsoon and monsoon months*

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ABSTRACT. For large scale convective activity there should be a combination of the following four favourable conditions—low level convergence, high level divergence, sufficient inflow of moisture in the lower levels and a favourable stability index. The synoptic models producing the above favourable conditions are discussed and the ways of identifying them on the daily working charts are indicated.

Thunderstorms during the monsoon season are caused by the movement of the upper easterly waves. The upper easterly and westerly wave troughs are compared and their relative efficacy in producing thunderstorms is commented upon.

Typical synoptic situations of thunderstorm activity in Bombay State during 1959 are given illustrative of the ideas mentioned in the earlier paragraphs.

Climatological distribution of thunderstorms and duststorms over India is explained in terms of the four favourable factors mentioned in the beginning.

Finally it is summed up that large scale convective activity occurs anywhere in India and the neighbourhood provided there is a proper combination of these favourable factors.

1. Introduction

1·1. The forecasting of thunderstorms in the simplified form is essentially a problem in the stability conditions of the atmosphere. However, forecasters have realised the inadequacy of the thermodynamic diagrams alone for this purpose. There are other factors mostly controlled by the kinematics of air motion, which have to be taken into account before any conclusions can be arrived at regarding the occurrence or otherwise, of thunderstorms. It is proposed to discuss in this paper these factors which have been found to be significant in the forecasting of large scale convective phenomena in the Indo-Pakistan sub-continent.

1·2. It is now well recognised that in any analysis (and prognostication) of weather, the atmosphere has to be considered as consisting of at least two layers and any synoptic discussion must take into account the processes taking place both in the lower as well as the upper layers (Riehl 1954a). In terms of a two layer atmosphere Petterssen (1955) has formulated a working hypothesis that "cyclonic development at sea level occurs when and where an area of positive vorticity advection in the upper troposphere becomes superposed upon a frontal zone at sea level". Koteswaram and Srinivasan (1958) in their study of the synoptic factors favourable for the occurrence of pre-monsoon thunderstorms in Gangetic West Bengal have also arrived at an almost similar conclusion, *viz.*, "for generation of thunderstorm activity over Gangetic West Bengal and by inference over the rest of northeast India, it is necessary to have suitable conditions for producing low level convergence as well as high level divergence and the occurrence of either of the conditions, by itself, is insufficient for setting off the thunderstorms". Some of the points described in the following paragraphs are based on the conclusions arrived at in that paper.

2. Favourable conditions for occurrence of large scale convection

2·1. The favourable conditions for large scale convective activity may be summarized as follows—

(*a*) A mechanism to cause low level convergence which will enable the

*Communicated to the Symposium on "Thunderstorms" held at New Delhi from 9 to 11 March 1960

lower layers of the atmosphere to ascend,

(*b*) High level positive vorticity advection causing divergence (or mass depletion) which will enable the lower ascending air to ascend further to very high levels,

(*c*) Sufficient inflow of moisture in the lower layers and

(*d*) A favourable lapse rate in the lower and middle troposphere.

The development of thunderstorms—except as a purely localized phenomenon—depends on the suitable combination of the above four favourable factors. Surface insolation and orography help the triggering of thunderstorms.

2·2. Favourable mechanisms causing low level convergence and typical upper air flow patterns causing appreciable vorticity advection are given in text books and earlier papers (Ramaswamy 1956, Koteswaram and Srinivasan 1958). It may be worthwhile to point that certain terms neglected in the expression for advection of vorticity in text books may not be justified in the conditions obtaining in the lower latitudes and these are precisely the terms which give rise to favourable upper air flow patterns, other than the jet stream trough, in the production of positive vorticity advection, as will be explained briefly in the next paragraph.

2·3. The expression for the advection of vorticity is :

$$A_Q = -V \frac{\partial Q}{\partial s}$$

where $Q = VK_s - \frac{\partial V}{\partial n} + f$

In the above equation A_Q is the advection of vorticity, Q=absolute velocity, V= wind speed, K_s =curvature of streamline, $\partial V/\partial n$=wind shear normal to the streamline being positive when wind speed increases to the left of the streamline looking downstream, and $\partial Q/\partial s$ = variation of Q along the streamline.

A gradient of vorticity along the streamline can be caused by the variation in the values of the three terms on the right hand side of the expression for vorticity,

$$Q = VK_s - \frac{\partial V}{\partial n} + f$$

In a westerly trough where the winds are strong, the contribution by the term VK_s is predominant so that the other two terms become negligible. In the case of a straight jet maximum, the contribution is solely by the second term $\partial V/\partial n$. In a northerly current with comparatively weak shear, the contribution is mainly by the term f, with the first term VK_s giving an additional contribution where the straight northerly stream turns anticyclonically. Thus the three different patterns in which the three different terms on the right hand side of the equation become by turn predominantly operative are the basic upper air configurations favourable for thunderstorm activity, with additional patterns arising out of the various possible combinations of the basic ones. In the case of the straight northerly current, it would appear that the inphase superposition of moving vortices and troughs are merely additional factors which strengthen the northerly flow, the primary cause of the variation of the vorticity still being the variation of the Coriolis parameter with latitude (Riehl 1954b, Riehl and Burgner 1950).

2·4. In the easterly troughs where winds are not strong, the effects of the variations in the relative velocity and Coriolis parameter combine to give large variations of absolute vorticity along the streamline. In contrast, in the upper westerly troughs where the winds are stronger, the variations in absolute vorticity downstream is controlled mainly by the variations in the relative vorticity (Petterssen 1956b). It has been noticed that although the upper

TABLE 1

Station	No. of thunderstorm days* with the 0300 GMT surface dew point being			Total No. of thunderstorm days (summer months of 51-59)
	above normal	normal	below normal	
Santacruz (Bombay)	26	4	7	37
Poona	93	6	15	114
Miraj	84	8	21	113
Ahmedabad	23	5	7	35
Total	226	23	50	299

*Days when thunderstorm, duststorm, hailstorm or squall occurred.

easterly troughs that pass across India are less pronounced than the westerly troughs, the weather caused by the former is still considerable. Hence even the weak easterly troughs deserve careful watch as they are potent agents in causing weather.

2·5. Koteswaram and Srinivasan (1958) have shown that thunderstorms fail to occur in Gangetic West Bengal unless there are southerly winds (advecting moisture into the area), at least upto 1·0 km a.s.l., in spite of the other conditions being favourable. The importance of the presence of moisture is brought out by an analysis of the surface dew point temperatures at four stations in the Bombay State—Santacruz (Bombay), Poona, Miraj and Ahmedabad. The days when thunderstorm, duststorm, hailstorm or squall occurred at these stations were classified with reference to departure from normal of the dew point temperature at 0300 GMT at the station. The analysis extended through the summer months for a period of nine years 1951-1959. The results are shown in Table 1.

It will be seen from Table 1 that when convective phenomena occurred the surface dew point temperature was, in the large majority of cases, above normal. It is significant to note that in the case of even a coastal station (Santacruz), where dew point temperatures vary little from day to day, thunderstorms occur only when the dew point temperatures are above normal. The thunderstorm days were found to be most frequent with the dew point temperature either normal or a few degrees (4 to 6°C) above normal. The non-occurrence of thunderstorms on a number of days with the surface dew point temperature above normal also indicates that mere incursion of moisture alone is not sufficient for the production of convective phenomena.

2·6. (*i*) In addition to the conditions described in the above paras, it appears necessary that there should be a suitable lapse rate in the lower and middle troposphere. Without a favourable lapse rate in the lower and middle troposphere, the conditions given in para 2·1 (*a*), (*b*) and (*c*) seem to produce only heavy rain without thunderstorms. This conclusion has been drawn mainly from the thunderstorm activity associated with upper easterly troughs moving across India during the monsoon months (see para below).

(*ii*) Srinivasan (1960) has shown that during the monsoon period the maximum number of thunderstorms over Calcutta is associated with the passage of upper easterly wave troughs. However, in the western half of the Peninsula, particularly along the west coast, the strengthening of the monsoon associated with the passage of the easterly waves is marked by heavy rainfall, without any noteworthy thunderstorm activity. This fact indicates the importance of the stability index in the forecasting of thunderstorms.

(*iii*) Fig. 1 shows the monthly mean values of the stability indices* over India for the months of April and May (Hot Weather Season) and July and August (Monsoon Season). The very low values of the stability indices along the west coast, particularly Konkan, compared to those over the rest of the country during the monsoon seem to point out the necessity for unstable lapse rate in the lower and middle layers of the atmosphere, for the occurrence of thunderstorms.

3. Illustrative examples

3·1. Ramaswamy (1956) and Koteswaram and Srinivasan (1958) have given a number of synoptic situations illustrating the role of the various factors such as jet stream trough, straight jet stream etc, in causing large scale convection in upper India. In this article, it is proposed to give a few recent examples of large scale and violent thunderstorms in the Bombay State, since such thunderstorms are not so common in this part of India.

3.2. *Widespread thunderstorms and squalls in Gujarat and Saurashtra on 18 April 1959*

(*i*) On 18 April 1959 widespread dust and thunderstorms accompanied by squalls occurred in Saurashtra and Gujarat. Ahmedabad recorded a maximum wind speed of 50 knots and Baroda 38 knots during the squall. Deesa also reported a northwesterly squall. According to newspaper reports, thundersqualls also swept over Rajkot, Bhavnagar and Jamnagar causing disruption of tele-communication services. In Mehsana district, in Gujarat, huts were blown off. The synoptic and upper air conditions on the morning of 18 April 1959 are shown in Figs. 2(a) to (d).

(*ii*) In the upper air there was a well marked trough with its axis over Kutch and Saurashtra between 6·0 and 9·0 km a.s.l. (Fig. 2a). The passage of this trough over Kutch, Saurashtra, Gujarat and west Rajasthan on the 18th was also confirmed from the vertical time sections of Veraval and Jodhpur.

(*iii*) In the lower levels, there was a cyclonic circulation at 0·9 and 1·5 km a.s.l. (Fig. 2b). It may be pointed out incidentally that 24 hours pressure changes over the area showed a general rise at 0300 GMT of 18th.

(*iv*) The stability index chart (Fig. 2c) showed relatively higher values of instability over Gujarat and the adjoining areas. There was also a pronounced incursion of moisture into the area as revealed by dew point isopleths (Fig. 2d). The dew points over the area were also much above normal.

(*v*) The weather realized over the area during the 24 hour period ending at 0300 GMT of 19 April 1959 is given in Fig. 2(e). An examination of charts given in Figs. 2(a) to (e) would clearly show that large scale violent convection took place over an area where there was a combination of all the favourable factors mentioned in para 2·1 above. The earlier outbreak of the thunderstorms and duststorms (see Fig. 2f) was over a narrow belt where such a combination was most effective, in the region of the "moisture jet" below (Fig. 2d) and the immediate vicinity of the trough line above (Fig. 2a).

*Stability indices have been worked out from the monthly mean values of temperatures at the various radiosonde stations in India. The index has been expressed as the difference in temperature(°C) of an ascending air parcel from the 850-mb level to 500-mb level, over the temperature of the environment at the 500-mb level. This figure will be positive if the environment at 500-mb level is colder than the ascending air parcel.

3.3. *Thunderstorms over north Maharashtra, Konkan and Gujarat on 27 April 1959*

(*i*) The synoptic charts for the morning of 27 April 1959 are shown in Figs. 3(a) to (d). In the upper air there was a jet maximum over Saurashtra. The average shear in the right entrance sector was nearly 13 knots per 100 km even at 9·0 km a.s.l. and extended upto Maharashtra (Fig. 3a). Although the isotachs have been more or less uniformly spaced in this diagram due to sparse data, it is to be borne in mind that the highest values of wind shear generally occur about 200 km away from the jet axis (Riehl 1954c). In the lower layers there was a cyclonic circulation over Maharashtra and north Mysore between 2·0 and 3·0 km a.s.l. (Fig. 3b). The stability index is shown in Fig. 3(c). The surface dew points are shown in Fig. 3(d).

(*ii*) The weather realised during the 24 hours ending at 0300 GMT of 28th is shown in Fig. 3(e). In this case also the combination of all the favourable factors produced thundersqualls and hailstorms. At Poona the maximum wind rose to 52 knots in squall; Bombay (Santacruz) also had a mild squall. It was reported in newspapers that the thundersquall caused failure of electric supply in Poona and also dislocation of train services between Lonavala and Poona. It is significant that although there was a 'moisture jet' over east Vidarbha, it did not cause any weather, since the other factors were not favourable there. All the thunderstorms were confined to the west of Long. 75°E.

(*iii*) The isochrones of thunderstorms showed that the outbreak occurred earlier in the central Maharashtra (Poona, Ahmednagar and Mahabaleshwar area) and only later on in Konkan; it is apparently due to the combination of all the favourable factors being most effective over central Maharashtra, and also due to the effects of orography and stronger insolation there.

3.4. *Thunderstorms over Maharashtra and Telangana on 22 May 1959*

(*i*) The high level agency in the production of thunderstorm on this day was the flow of a northerly current of air over the Indian Peninsula which had been accelerated by an anticyclone over Saurashtra and a cyclonic vortex in the southwest Bay of Bengal (Fig. 4a): this is a situation almost similar to the high tropospheric flow pattern prior to the formation of tropical cyclonic storms (Riehl 1954b). The low level convergence in this case was caused by the wind discontinuities at 1·5 and 2·1 km a.s.l. in the northern half of the peninsula and by the decrease of wind downstream below 1·0 km a.s.l. over the south Peninsula (Fig. 4b). The inflow of moisture is shown in Fig. 4(d) and the stability index in Fig. 4(c). The actual weather realised during the 24 hours period ending at 0300 GMT of 23rd is shown in Fig. 4(e). Newspapers reported that the severe thunderstorms caused havoc in two talukas in Ahmednagar district. Three persons were killed and about sixty injured due to tin roofs blown off during the thunderstorms.

3.5. *Thunderstorms associated with the passage of upper easterly trough*

The occurrence of a heavy thundershower over Bombay on 2 June 1959, is shown in Fig. 5(a) by the vertical time section for Bombay. The thundershower coincided with the passage of the upper trough over the station. Nearly 9 cm of rain fell between 1200 and 1800 GMT during the thunderstorm. Earlier during the day there was also a squall.

The weather realized during the 24 hour period ending at 0300 GMT of the 3rd over the whole country is also shown (Fig. 5b). The region of thunderstorm activity on this day can be divided into three broad areas—(*i*) ahead of the westerly trough in northeast India and east Madhya Pradesh, (*ii*) close to and ahead of an easterly trough over the western half of the Peninsula and

TABLE 2

Season and month	Locality of high frequency of thunderstorms and duststorms	Synoptic conditions producing: Low level convergence	Synoptic conditions producing: High level positive vorticity advection	Influx of moisture into low levels	Seasonal stability index
(1)	(2)	(3)	(4)	(5)	(6)
1. Summer (April and May)	(*a*) NE India outside Bihar and East Pakistan	(*i*) Formation of low over Chotanagpur area, or passage of secondaries of western disturbances (*ii*) Accentuation of seasonal low or its extension eastwards (*iii*) Convergence in the southerly winds in lower layers due to variation of wind speed or curvature of streamline or both	Passage of westerly troughs, jet maxima, and jet stream trough	From the Bay of Bengal around the low or the seasonal trough mentioned in col. 3.	Favourable
	(*b*) Western half of south Peninsula	(*i*) Seasonal low generally accentuated in the evening (*ii*) Passage of low pressure waves from the east	Passage of easterly waves Flow of straight northerly currents in upper levels	Both from the Bay and the Arabian sea on account of the seasonal low and the passage of easterly trough	Do.
2. Monsoon (June, July, August and September)	(*a*) Gangetic West Bengal, Orissa, Chotanagpur and northeast Madhya Pradesh	(*i*) Passage of monsoon depressions (*ii*) Convergence along the axis of the monsoon trough	(*i*) Passage of easterly waves	The area is in the field of monsoon current	Do.
	(*b*) Punjab (Pakistan), north Rajasthan and adjoining west Uttar Pradesh	(*i*) Passage of western disturbance earlier in the season and monsoon depressions later (*ii*) Wind discontinuity between monsoon air and dry continental air	(*i*) Passage of westerly waves and occasionally easterly waves	Influx of monsoon air in association with monsoon depressions : earlier in season influx of moisture from the Bay of Bengal and occasionally from Arabian Sea due to passage of western disturbances	Do.
3. Post Monsoon (October and November)	South Peninsula, south of lat. 13°N	(*i*) Passage of low pressure waves from the east (*ii*) Wind discontinuity between the retreating monsoon air and northeast trades	Passage of upper easterly waves	In the field of monsoon air	Do.

(*iii*) over a region of a northerly current in east Rajasthan and Gujarat, which has been apparently intensified by an anticyclonic vortex over Sind and the easterly wave over south Peninsula.

4. Climatological aspects

Climatological charts (India met. Dep. 1943) show that over India and Pakistan the frequency of thunderstorms and duststorms is high in certain areas in particular months. Such areas are given seasonwise in Table 2 together with an explanation for this high frequency of thunderstorms in terms of the four favourable synoptic factors discussed in para 2·1.

5. Conclusion

5·1. The occurrence of large scale convective phenomena is conditioned by the favourable combination of the factors mentioned in para 2·1. Irrespective of season and locality, it is the combination of the various favourable conditions that determine the outbreak of thunderstorms. The reason for the high frequency of thunderstorms in northeast India in the pre-monsoon season is due to the combination of the favourable conditions being common in northeast India in that season. In the other parts of India also the same conditions are favourable for the development of large scale convection, but the number of occasions of such combination is less than in northeast India in the pre-monsoon season.

5·2. We may think of the stability index as the factor indicative of the instability conditions in the atmosphere, and the lower convergence and upper advection of vorticity as processes responsible for the modification and the realisation of the instability. There is, of course, the necessity for moisture, as otherwise no clouds can form. However, it is possible that even a initial shallow layer of moist air can become deep due to the stretching of the lower layer by convergence.

5·3. While the pre-monsoon thunderstorms of upper India are generally of a violent nature, the thunderstorms of the south Peninsular India are only very occasionally associated with severe squalls etc. Out of the four favourable factors for the occurrence of thunderstorm, there can hardly be any difference between the Peninsular India and northern India in the low level convergence. Monthly seasonal values of stability index also show only slight differences between the extreme south Peninsula in April and northeast India and the adjoining areas in May. Hence one is led to think that the agency producing the violence of the thunderstorms is either the upper tropospheric flow pattern or the higher moisture content or a combination of both, although this requires further study..

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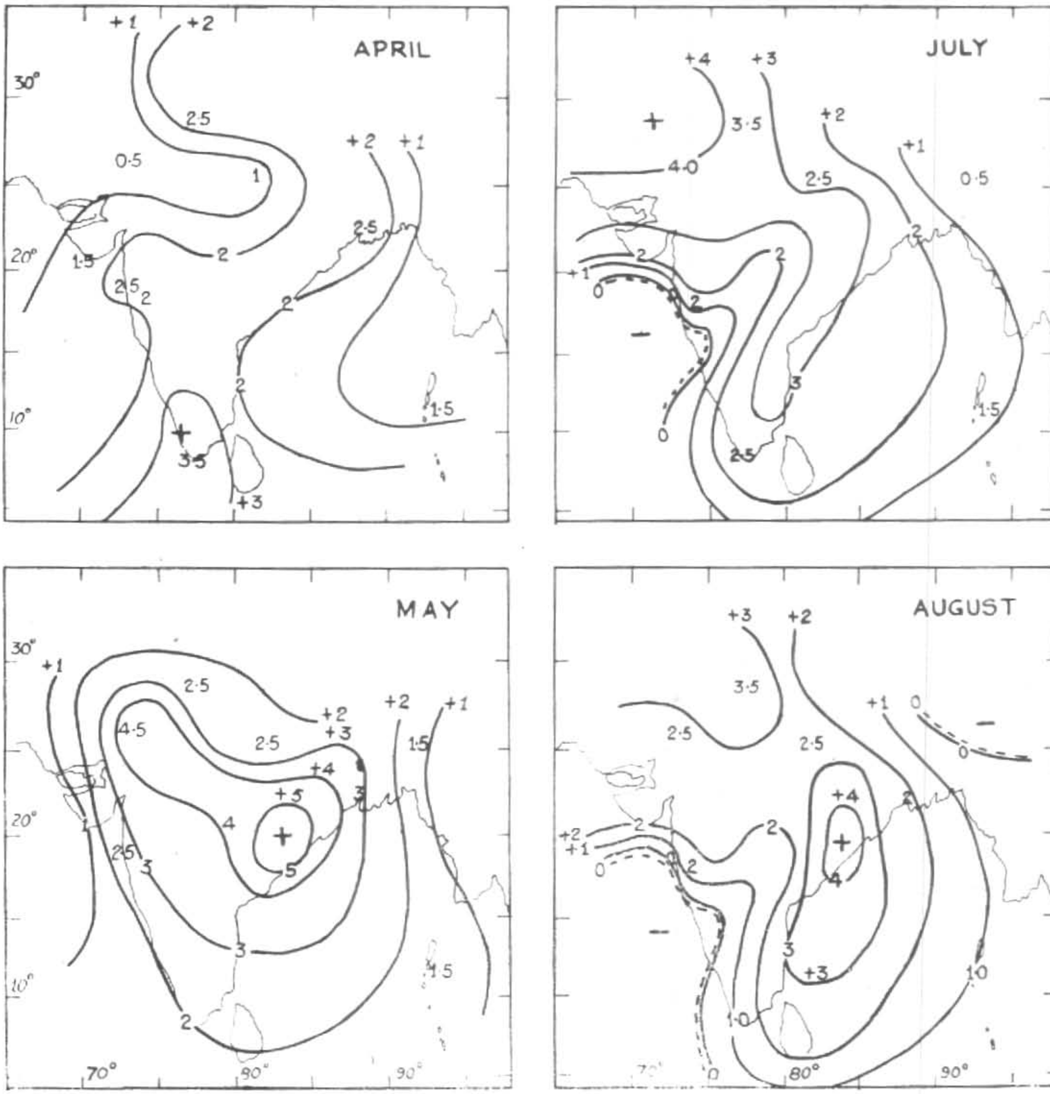

Fig. 1. Mean monthly values of stability indices

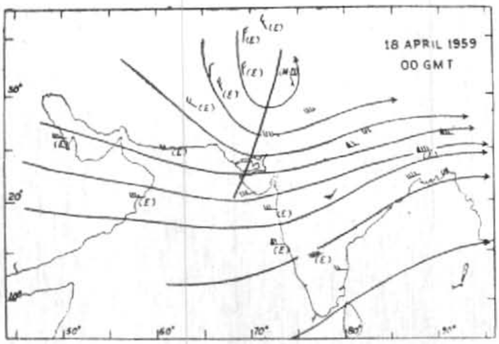

Fig. 2(a). Streamlines at 9·0 km

Thick line—trough line, (E)—evening (1200 Z) winds, (M.D.)—Midday (0600 Z) winds. Dashed winds refer to next lower level

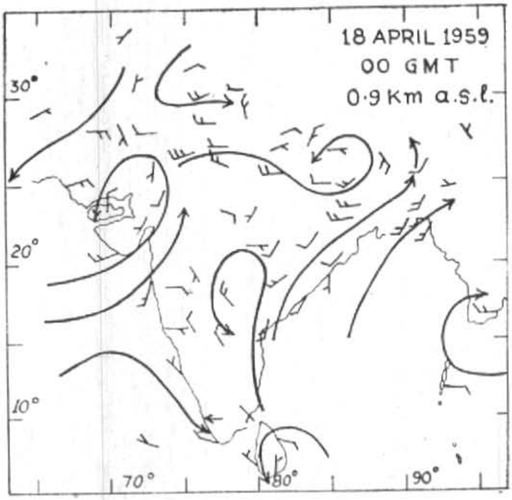

Fig. 2(b)

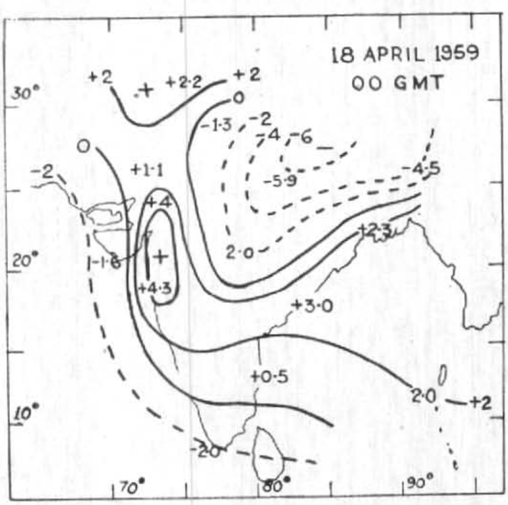

Fig. 2(c). Stability index

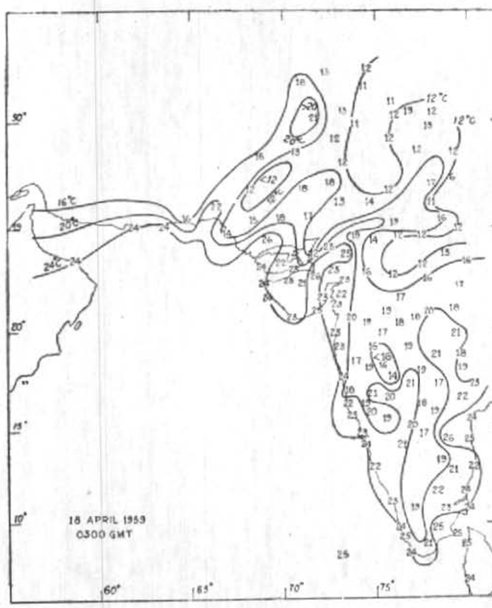

Fig. 2(d). Dew point temperatures (°C)

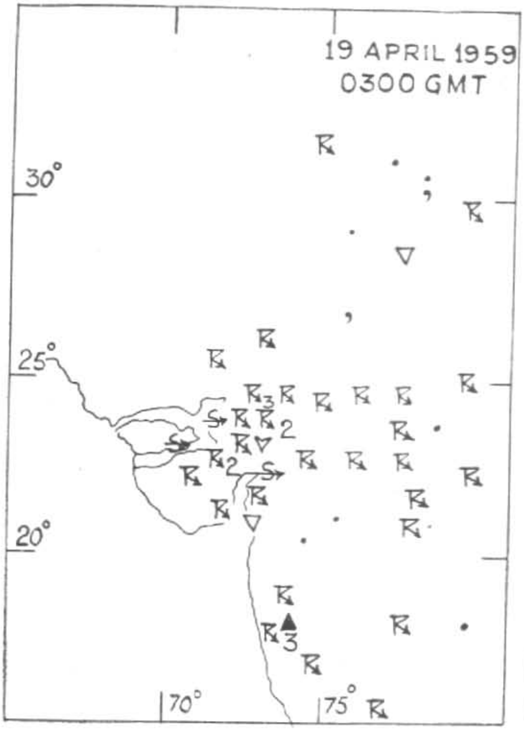

Fig. 2(e). Past weather in last 24 hours
(Rainfall below 2 cm not shown)

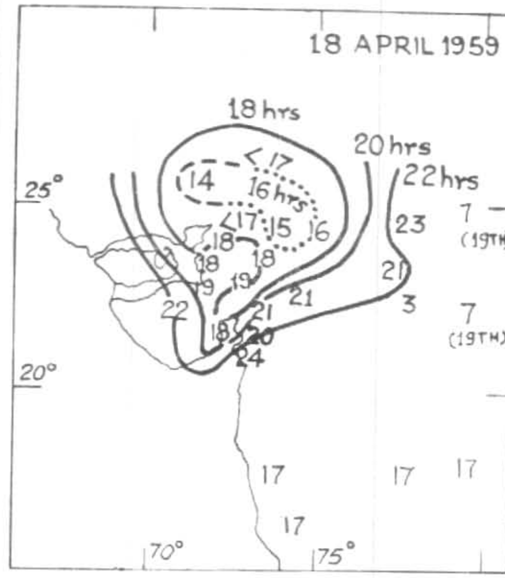

Fig. 2(f). Isochrones (IST) of thunderstorms

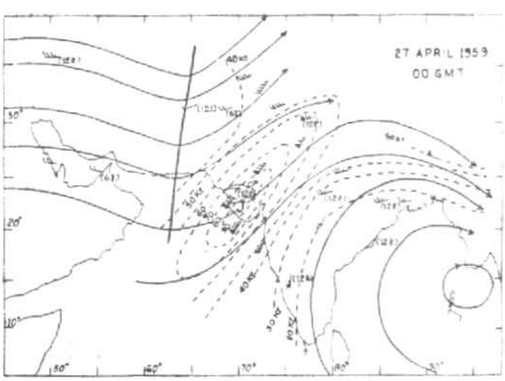

Fig. 3(a). Streamlines and isotachs at 9·0 km
(Thick line—trough line)

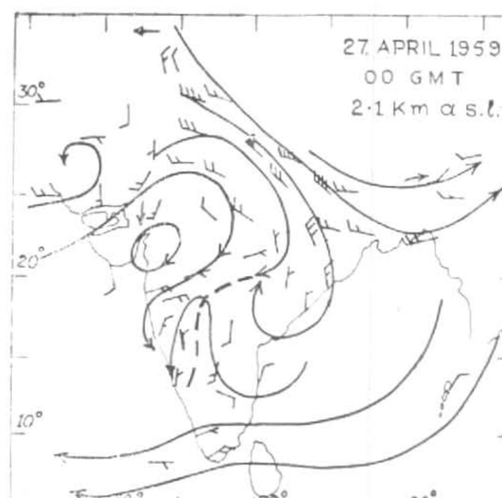

Fig. 3(b)

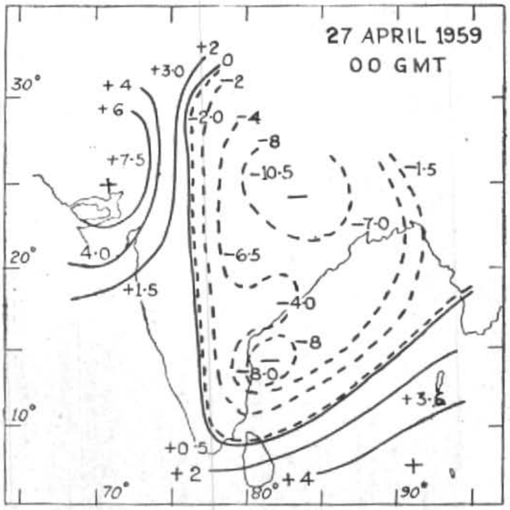

Fig. 3(c). Stability index

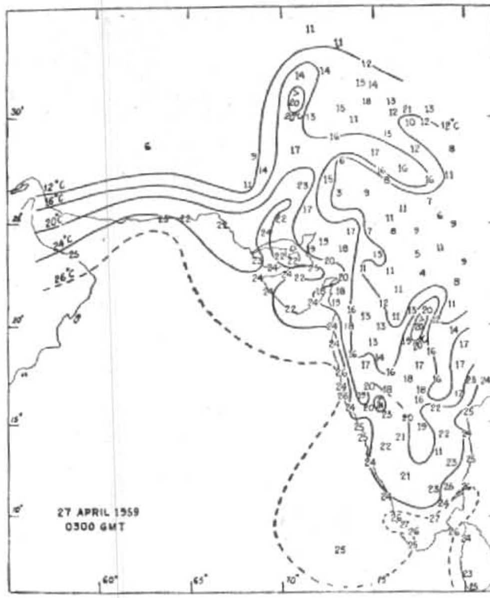

Fig. 3(d). Dew point temperatures (°C)

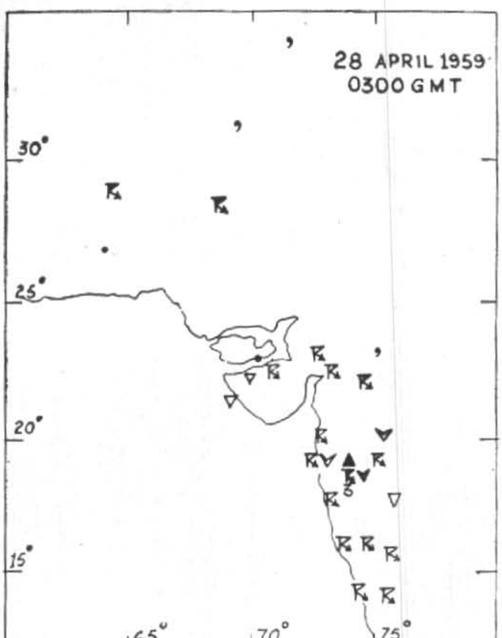

Fig. 3(e). Past weather in last 24 hours

(Rainfall below 2 cm not shown)

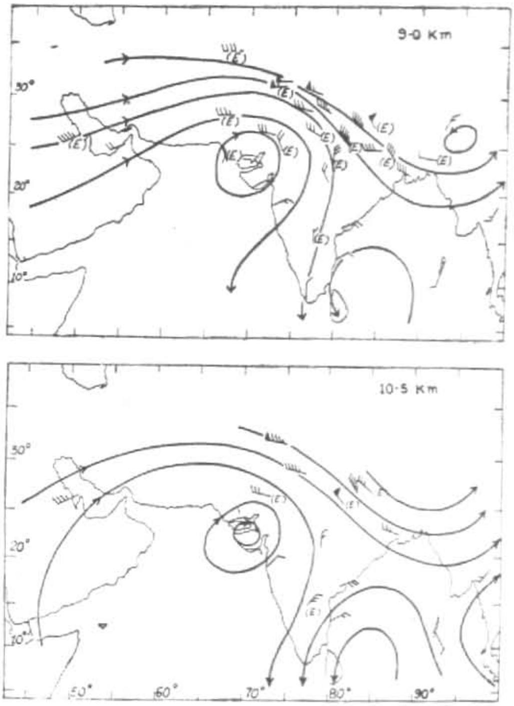

Fig. 4(a). Streamlines on 22 May 1959, 00 GMT

(E)—1200 GMT winds. Dashed winds refer to next lower level

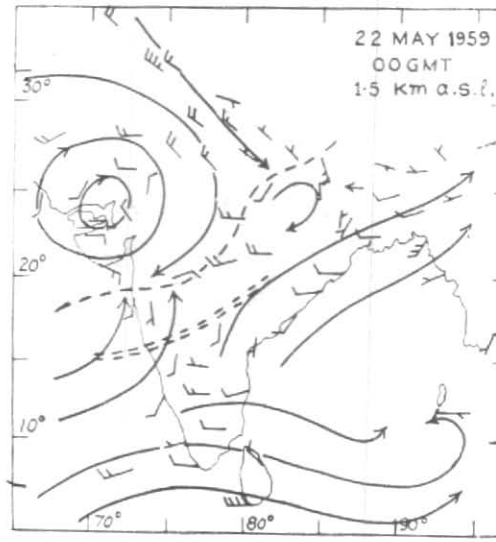

Fig. 4(b)

— — — wind discontinuity at 1·5 km a.s.l.
= = = same at 2·1 km a.s.l.

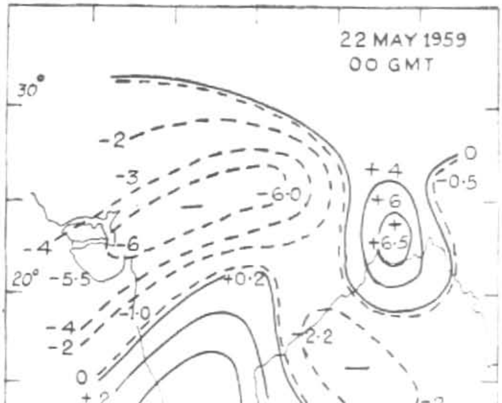

Fig. 4(c). Stability index

Fig. 4(d). Dew point temperatures (°C)

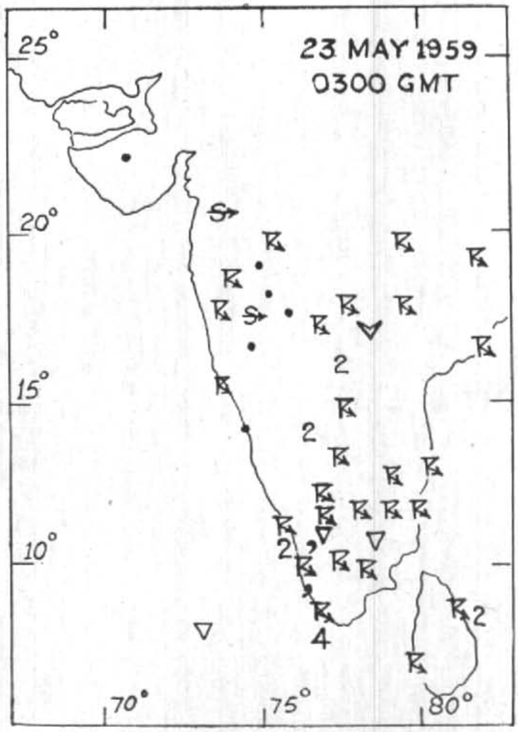

Fig. 4(e). Past weather in last 24 hours (Rainfall below 2 cm not shown)

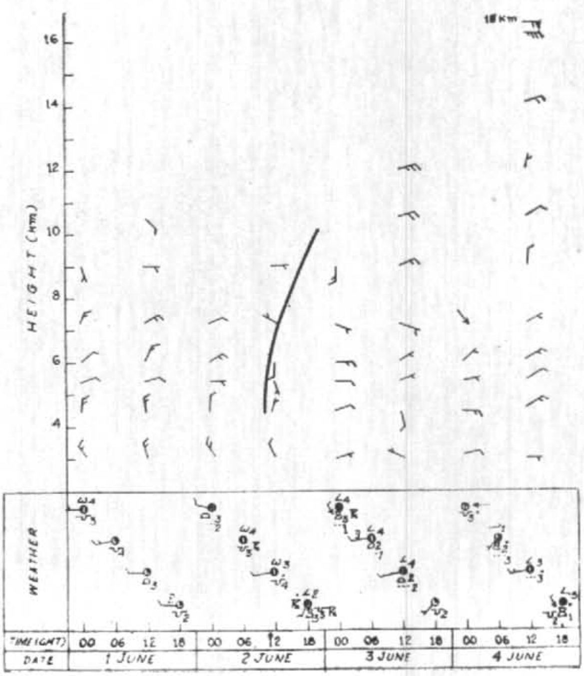

Fig. 5(a). Vertical time section—Bombay: 1-4 June 1959

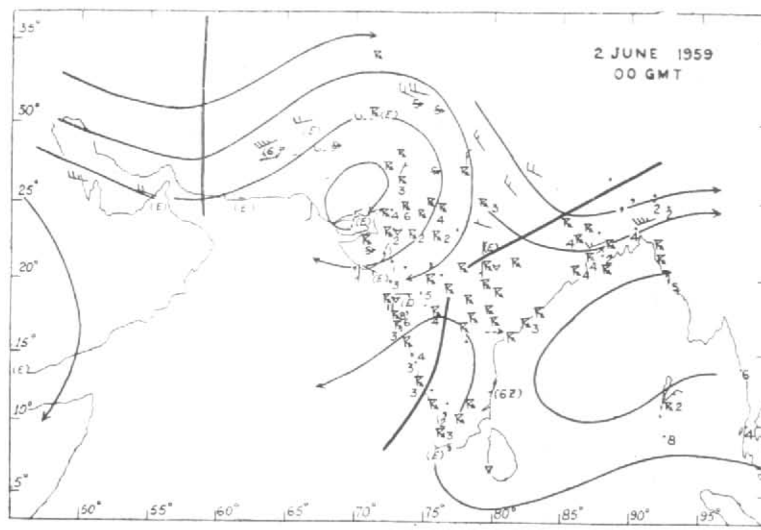

Fig. 5(b). Winds and streamlines at 9·0 km a.s.l.

(E)—1200 GMT winds, dashed winds—lower level winds, thick lines—trough lines. The weather realised during the 24 hours ending at 0300 GMT of 3rd is also shown. Rainfall amounts are given in cm. Rainfall amounts less than 2 cm not shown.