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FORECASTING MANUAL

PART III

DISCUSSION OF TYPICAL SYNOPTIC WEATHER SITUATIONS

2·2 SUMMER-NOR'WESTERS AND ANDHIS AND LARGE SCALE CONVECTIVE ACTIVITY OVER PENINSULA AND CENTRAL PARTS OF THE COUNTRY

BY

V. SRINIVASAN, K. RAMAMURTHY AND Y. R. NENE

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FORECASTING MANUAL

Part III - Discussion of Typical Synoptic Situations

2.2 Summer - Nor'westers and Andhis and Large Scale Convective Activity over Peninsula and the Central Parts of the Country

by

V. Srinivasan, K. Ramamurthy and Y.R. Nene

Contents:

1. Introduction

1.1 According to the Departmental classification of the year into seasons, March, April and May constitute the 'Hot Weather Period'. It is also known as the 'Pre-Monsoon Season . In an earlier report - FMU Rep. No. III - 2.1 we have discussed the weather over the Indian sea areas during this season. In the present report, we will take up the weather over the land areas.

1.2 The hot weather period is known for its intense convective activity over land areas. Apart from depressions and cyclonic storms that form over the Indian sea areas and move towards the coast affecting the land areas, the only other weather phenomenon during this season is the convective type of weather (thunderstorms, duststorms, hailstorms and their associated features).

1.3 Thunderstorm is a very vast subject. Considerable work has been done in this field during the past 2 to 3 decades and a large amount of literature is now available on this subject. The different aspects of the subject include structure and the physics of the thunderstorms, synoptic and climatological aspects, radar and satellite studies etc. In this Forecasting Manual Report we will confine ourselves to the synoptic aspects with special reference to the forecasting of thunderstorms. Climatological, radar and satellite studies will be briefly touched upon in so far as they are relevant to the forecasting of thunderstorms.

1.4 Excluding the days of cyclonic storms and depressions (which will be only a few in number), the day-to-day clouding and weather during the hot weather season is mainly over land and considerably less over the sea areas. Development of clouds and weather also shows marked diurnal variation.

1.5 The main regions of high thunderstorm activity in our country during the pre-monsoon season are:-

i) the area stretching from Assam and adjacent states to East Madhya Pradesh, east Vidarbha and adjoining Andhra Pradesh.

ii) Southwest Peninsula

iii)Northwest India outside Rajasthan

Over these areas, there are over 15–20 thunderstorm days, on an average, in this season. They are as much as 30–40 days in Assam and adjacent states and in south Kerala. Although no part of the country is free from thunderstorm activity during this season, the minimum activity is in Gujarat State – where the number of thunderstorm days hardly exceeds five for the whole season. This seasonal pattern of thunderstorm activity over the country holds good in the individual months also; but the activity progressively increases from March onwards as the season advances. While in March, the mean number of days of thunderstorms is not more than 6–8 in any part of the country, it reaches 14–16 days in Assam and adjacent areas and in Kerala in May. Though thunderstorm activity may continue over the country even during the monsoon season, the severity of the thunderstorms is marked only in the pre-monsoon season when they are, on a number of occasions, accompanied by squalls. There have been some instances in the past when even trains have been thrown off the track by violent thundersqualls.

2. Climatology of India during the Pre-Monsoon Season

2.1 In the beginning of the pre-monsoon season, the sea level pressure pattern is diffuse over the country and the gradients are slack. As the season progresses, the heat low develops over north India and it takes a definite shape only during the second half of the season. In the early part of the season (i.e. March), the heat low may be seen over interior south Peninsula, particularly in the evening charts. Progressively it shifts north and in April, the heat low is over northeast Madhya Pradesh and the adjoining south Uttar Pradesh. Towards the end of the season, it extends as a trough from northeast Rajasthan, Punjab and Haryana to southeast Uttar Pradesh and the adjoining northeast Madhya Pradesh. On account of the increased insolation during the day, the heat low becomes more marked in the afternoon and evening. With the centre of the low pressure system in the interior of the country and the anticyclonic cells over the sea areas – one over the Arabian Sea and the other over the Bay – the isobars generally run parallel to the coast.

2.2 The heat low is very shallow and no well-defined cyclonic circulation corresponding to the heat low appears in the low levels in the upper air. However, quasi-stationary wind discontinuities are present, the prominent discontinuity line during this season being the one running north-south over the Peninsula. It frequently joins up with the other discontinuity over northeast India, which is usually present from southeast Madhya Pradesh to Assam and Meghalaya and Nagaland. In the first half of the season when the winds are weak, sea breeze effect is well-marked. As the season advances, westerlies begin to predominate in the lower troposphere and they gradually strengthen. In the mid- and upper troposphere, the winter-time westerlies continue to hold sway over north India. These westerlies strengthen with height and reach jet strength at higher levels (250–200 mb). Jet streams and troughs in westerlies are the common features of the upper westerly flow over north India during this season.

2.3 The lapse rates of temperature are fairly high over a large portion of the country. The highest lapse rates in the lower and middle troposphere are over Madhya Pradesh, Uttar Pradesh and Rajasthan where they reach almost dry adiabatic values. The lapse rates decrease considerably towards the east (northeast India) and south (south Peninsula). There is a very large horizontal gradient in lapse rate distribution over Bihar and Orissa and these large gradients play a role in the destablization of the atmosphere due to differential thermal advection (as explained in para 25.16.2 d of Petterssen "Weather Analysis and Forecasting" – Vol.2).

2.4 Thus the main features of the atmospheric conditions over the country during this season are:–

i) Intense insolation and large diurnal variation of many meteorological parameters

ii) Formation of a heat low over the interior of the country

iii) Weak to moderate lower tropospheric wind field overlain by a moderate to strong westerly flow (except over the Peninsula where in the upper troposphere also the winds are generally light to moderate).

iv) High degree of instability in the atmosphere

v) General lack of moisture, except in the lowest levels over some parts of the country.

3. Conditions favourable for the occurrence of thunderstorms – General Discussion

3.1 Thunderstorm is usually classified as a 'meso-scale' phenomenon with its space scale between a few and a few hundred kilometres and its time-scale from a few minutes to a few hours. Though thunderstorms are one or two orders of magnitude less than the synoptic disturbances, the development of thunderstorms is greatly governed by the overall synoptic scale disturbances. It is the synoptic scale disturbances which create the conditions favourable for the out-break of thunderstorms.

3.2 The synoptic and aerological conditions favourable for the occurrence of convective type of weather can be broadly stated as follows:-

i) conditional and convective instability in the atmosphere

ii) adequate supply of moisture, particularly in the lower levels

iii) a dynamical mechanism to release the instability present in the atmosphere; in this may be included the mechanism for lifting the air as well as for destabilising it by suitable advective processes.

3.3 The degree to which these conditions are present and the synoptic situations causing the favourable conditions differ from region to region. It will be, therefore, more advantageous to discuss this, regionwise. For this purpose we may divide the country into four broad divisions:-

i) Northeast India

ii) Northwest India and Uttar Pradesh

iii) Central parts of the country and

iv) Peninsula

In the following pages we will discuss the occurrence of thunderstorms and the associated synoptic situations, divisionwise, illustrated by typical examples.

4. Thunderstorms in Northeast India – General

4.1 Northeast India is one of the areas of high frequency of occurrence of thunderstorms in this country. Thunderstorm activity starts in northeast India in March and reaches its maximum phase in May, both in terms of number of days of activity as well as spatial distribution. However, there are differences in the activity from sub-division to sub-division. In Assam and adjacent states, the activity is fairly high in all the three months. In these areas, there is a considerable increase from March to April; and it increases further only slightly in May. In the other sub-divisions of northeast India except Bihar Plains, the activity in May is almost double that in April. In Bihar Plains, thunderstorm activity is mainly in May. In spatial distribution also, the activity is more in Assam. Bihar State generally gets only isolated to scattered activity.

4.2 For our purpose of discussion of thunderstorms during the hot weather period, northeast India may be further sub-divided into two areas:-

i) Sub-Himalayan West Bengal and Assam and adjacent states

ii) Gangetic West Bengal, Bihar State and Orissa.

To the second group of sub-divisions we may add the adjacent areas of East Madhya Pradesh also.

4.3 The thunderstorms of northeast India are known as 'Nor'westers' and they are associated with moderate/severe squalls, which may reach tornadic violence causing considerable damage to property and even loss of life. Tornadoes occur in northeast India on very rare occasions. West Bengal and Assam and adjacent states are the areas most susceptible to tornadoes; and even here, tornadoes are reported only once in a few years. The "Nor'westers of Bengal" have been extensively studied by the Indian Meteorologists and a considerable volume of literature exists on the subject.

5. Thunderstorms in Gangetic West Bengal, Bihar State and Orissa

5.1 General

5.1.1 Some of the commonly known features about the nor'westers in Gangetic West Bengal, Bihar State and Orissa are as follows:-

i) The frequency of thunderstorms increases from March onwards to May. April and May account for most of the thunderstorms. Bihar Plains have much less activity than the other meteorological sub-divisions in this group.

ii) A majority of these thunderstorms are associated with squalls, the frequency of squalls increasing as we go from northwest to southeast. The squalls are mostly from a northwesterly direction. The highest speeds reached in these squalls are in the order of 140-150 kmph.

iii) There is a definite time sequence for the thunderstorms. They generally develop over Bihar Plateau, southeast Madhya Pradesh or west Orissa and travel east or southeastwards towards Gangetic West Bengal or head Bay of Bengal. They do not advance more than 80/100 miles (130-160 km) into the sea.

iv) The thunderstorms that occur in West Bengal and the adjoining areas have been classified into four types - A, B, C and D - in I.Met.Tech.Note No.10 (1944).

Type A thunderstorms develop over Bihar Plateau and the adjoining areas, mainly in the afternoon, and subsequently move in a southeasterly direction

Type B thunderstorms originate in the submontane districts of north Bengal and move southwards. They are generally during night and early morning.

Type C thunderstorms originate in the hills of Nagaland, Manipur and Mizoram and travel westwards. They are very rare.

Type D is very similar to type B but the place of origin is near the Khasi hills and not the Himalayas. The direction of movement is also from north to south

In a special investigation of the pre-monsoon thunderstorms in northeast India made by the Department in April - May 1941, it was found that a large majority of thunderstorms that occurred in Bihar and Gangetic West Bengal was of A type. Nearly 80% of the thunderstorms were of A type, while hardly 10% was of the B type, the other types accounting for the rest. In a study of thunderstorm-squalls at Calcutta (Rao and Boothalingam 1957) it was found that two-thirds of the nor'westers of A type was preceded by thunderstorms both at Hazaribagh and Asansol while the remaining were preceded by thunderstorms at Asansol. Their speed of travel was roughly between 30 and 40 mph (about 50 to 60 kmph).

5.2 Conditions favourable for the occurrence of thunderstorms.

5.2.1 As we have mentioned earlier in para 3.2, the conditions favourable for the occurrence of convective activity are in general:-

i) conditional and convective instability in the atmosphere

ii) adequate supply of moisture in the lower troposphere

iii) suitable synoptic conditions to cause low level convergence and upper level divergence which will act as a trigger and release the instability present in the air mass.

iv) suitable upper air flow which by advecting warm air in the lower troposphere and cold air in the upper troposphere can increase the instability

v) Daytime heating, orography etc.

5.2.2 Though each one of the conditions is considered favourable for convective development, their relative importance and the weightage to be given to each factor have not yet been clearly established. Thus, any discussion on this will have to be only qualitative and in general terms. We shall now discuss each one of the favourable conditions in some detail.

5.3 Conditional and convective instability

5.3.1 The presence or absence of conditional and convective instability is deduced from the tephigrams. Over the area comprising of Gangetic West Bengal, Orissa and Bihar State, we have two radiosonde stations (Calcutta and Bhubaneshwar) which have to be taken as representative of the area. Besides, in assessing the instability and making use of the tephigrams for forecasting purposes, one has to take into account the changes likely to take place in the thermodynamic structure of the atmosphere over the area by the forecast time, caused by insolation, advection etc. Except for the changes in the lowest level temperature profile caused by surface heating, it is difficult to assess the other changes in the tephigram objectivity and hence these changes have only to be qualitatively taken note of. Sometimes low level convergence is taken into account by lifting the entire air by about 50–100 mb (U.S. Weather Bureau, Forecasting Guide No.1).

5.4 Stability Index

5.4.1 It is customary to quantify the instability present in the atmosphere by an index called 'stability index'. Some of the indices used are:-

(a) Showalter Index:

This index is the difference between the observed 500 mb temperature and the temperature that an air parcel at 850 mb would acquire if it were lifted dry adiabatically to its lifting condensation level and then moist adiabatically to 500 mb.

Since this takes into account the moisture at only one level (850 mb), improvements have been suggested to obtain a better index by taking into account more representative values of the low level moisture.

(b) Ramalingam Index:

In his 'Convective Turbulence Theory of Thunderstorms' Ramalingam (1960) has suggested that the critical condition given by the expression

$$\frac{\log \frac{P_1}{P_o}}{\log \frac{\theta_o}{\theta_1}}$$

should exceed the value 19 for thunderstorms to occur, where P_o is the pressure (mbs) at the ground and P_1 = 500 or 600 mb. θ_o and θ_1 are the corresponding potential temperatures (in °A). Ramalingam Index does not take into account the moisture content of the air.

(c) Total Totals Index:-

Recently in USA, the use of a new stability index called 'Total Totals Index', has been introduced. This index is the sum of the following two indices:-

i) Vertical Total Index which is defined as

$$T_{850} - T_{500}$$

ii) Cross Total Index which is defined as

$$T_d\ 850 - T_{500}$$

The advantage in the Total Totals Index is that it can be computed without actually drawing the tephigram. The Total Totals Index takes into account both the dry bulb temperature distribution and the moisture in the lower levels.

5.4.2 In using these index values, we must note that the critical values of the index change from region to region and from season to season. Extensive studies are required to determine these critical values.

5.4.3 In India, some workers have studied the problem and have determined the values of Showalter Index favourable for thunderstorm activity for some individual stations. With the recent few years data, a brief study was made to determine the Total Totals Index favourable for thunderstorm activity, in respect of a few stations. In the case of Calcutta and Gauhati, the Total Totals Index did not show any significance, though in the case of New Delhi the results were more encouraging. In the case of Gauhati and Delhi, even Td 850 by itself was found to be quite significant. This will be discussed later in detail. When the indices at the various R.S. stations are plotted on a chart and isolines are drawn, we may be able to locate potential areas of thunderstorm activity.

5.5 Typical Radiosonde Ascents

5.5.1 Even a casual run through the daily tephigrams of Calcutta for the season shows

i) the presence of both conditional and convective instability

ii) a shallow layer of moist air near ground, the depth usually not exceeding 50 to 100 mb on many days.

5.5.2 An analysis of the daily tephigrams (00Z) of Calcutta during the period (April and May of 1968–71) with reference to the moist layer and the inversion above it was made and the results are given below:

TABLE – I

	No.of days with thunderstorms in Gangetic West Bengal or Bihar Plateau	No.of days of no thunderstorms in Gangetic West Bengal or Bihar Plateau	Total
Moist layer close to ground with inversion above it	74	65	139
Moist layer in the mid-tropospheric levels	21	22	43
No moist layer at any level	12	40	52

It will be seen from the statistics that the low level moisture with an inversion above it, is the most common type and is also associated with a high percentage of thunderstorm days. Days with no moist layer at any level are predominantly dry.

5.5.3 A typical Radiosonde ascent of Calcutta (00Z of 21 April 1969) on a day of nor'wester is given in Fig. 5.1. On this day, fairly widespread thunderstorms occurred in Gangetic West Bengal and Bihar Plateau and isolated thunderstorms in Bihar Plains. Calcutta also experienced a thunderstorm with squalls, speed reaching 106 kmph. The rainfall at Calcutta for the 24 hour period ending 0300Z of 22nd was 9 cm.

5.5.4 An analysis of the 850 mb dew point temperatures of Calcutta (00Z) for the period April–May 1968–72 and the realised thunderstorm activity over Gangetic West Bengal and Bihar Plateau is shown in Table II.

TABLE - II

Frequency of Td Td values (00Z) at 850 mb level over Calcutta in relation to thunderstorm activity in the subsequent 24 hrs. over Gangetic West Bengal and Bihar Plateau

(Period of data:April and May 1968–72)

Range of Td Td (°A)	Total No. of occasions	No. of non-thunderstorm days	No. of thunderstorm days
<278	77	55(71)	22(29)
278–285	150	85(56)	65(44)
>285	63	23(37)	40(63)

(Figures in brackets indicate %)

The table brings out the fact that as the lower tropospheric moisture increases, the chances of thunderstorm activity become more.

5.5.5 The upper air flow over Gangetic West Bengal and the adjoining areas is one with a shallow layer of southerlies/southwesterlies from the Bay near the ground and west/northwesterlies of continental origin above. The layer of transition between the two air streams, is stable (with an inversion sometimes) in which moisture decreases very rapidly with height. The stable layer or inversion and the extreme dryness of air above the inversion, are by themselves not favourable for development of convective clouds.

5.5.6 Although the low level inversion inhibits the growth of convective clouds, it has an important role to play in the production of nor'westers. Its presence prevents the penetration of convection from the lowest moist air into the layers above. "Thus the moist layer can be increased in warmth and moisture content, so long as it does not become potentially warmer than the inversion. This permits a progressive increase of potential instability. Finally on the introduction of a mechanism to remove the inversion, an explesive overturning can take place" (Newton, 1962).

5.5.7 Under suitable synoptic conditions, the flow of moisture in the low levels can become quite pronounced. The use of the pressure difference between Calcutta and Barisal as a parameter to forecast nor'westers in Gangetic West Bengal, used in early days in India, is only another way of quantifying the moist southerly flow from the Bay into Gangetic West Bengal. It is well-known that the nor'westers are more frequent and usually more severe in Bangla Desh than in Gangetic West Bengal – which is attributed to increased moisture content in the lower levels over Bangla Desh.

5.5.8 Thunderstorm development is a rapid process occurring within a short period of a few hours. Prior to this development, there is a continuous and gradual change in the atmospheric conditions and the conditions just before the time of occurrence of the thunderstorm may be very different from the conditions earlier at the time of the routine radiosonde ascent, say at 0000Z.

5.5.9 In USA, the atmospheric soundings representative of the air masses in which tornadoes occur have been studied and four different types of "mean soundings" have been identified. The sounding designated as Type I in the U.S. studies is very much similar to the typical sounding over Calcutta during the norwester season, described earlier in para 5.5.3 and Fig. 5.1. This sounding is characterised by dry air overlying a shallow layer of moist air near the ground, with a stable layer or inversion in between and exhibiting convective and conditional instability. However, when soundings close to (within 50 miles of) the place of the tornado and within an hour prior to the occurrence of the tornado were examined, it was noticed that

i) the typical inversion had disappeared and

ii) the moist layer has become deep, reaching as much as 16000 ft agl on an average.

This sounding is called the "proximity sounding". Comparing the proximity sounding with the mean sounding, it is clear that the proximity sounding represents conditions over a relatively small area and reveals the changes in environment associated with the tornado development. A typical "proximity sounding" for Calcutta is given in Fig. 5.2 (1200Z ascent of 17 April, 1969). A nor'wester passed over Calcutta within an hour of the ascent.

5.5.10 In India, forecasters using the tephigrams for predicting nor'westers in Gangetic West Bengal recognised the inadequacy of the morning radiosonde ascents and concluded that "the factors which bring about the modifications in the atmospheric structure appear to be of a more local character and may not, therefore, be indicated always by soundings made 6 or 12 hours earlier"(Roy,1959).

5.5.11 The above discussion would, therefore, suggest that (i) additional radiosonde ascents and (ii) ascents at more stations in northeast India may be necessary to understand nor'westers better and to aid the forecasters.

5.6 Moisture

5.6.1 Conditional and convective instabilities are the preconditions for development of nor'westers, and they depend upon the distribution of moisture along the vertical. It has been found that the distribution of moisture in the horizontal is also equally important.

5.6.2 The horizontal distribution of moisture at the ground level is indicated by an analysis of dew point temperatures reported by the surface observatories. From an analysis of the horizontal distribution of moisture, we may be able to locate regions of moisture concentration. The distribution of moisture at the various levels in the upper air may be had from the radiosonde data. But, without a dense radiosonde network, delineation of moisture distribution at the various standard levels in the upper air may not be quite objective.

5.6.3 One of the features of the synoptic charts on thunderstorm days has been the injection of moisture along a relatively narrow band or finger. Though we do not have a close radiosonde network to identify such narrow bands of moisture* in the upper air charts, surface dew points clearly bring out the existence of such moisture bands or fingers.(see Fig. 5.3 for a typical case). The initial outbreak of thunderstorms usually occurs in the zone of steep moisture gradient in association with such fingers of intruding moisture, particularly when the gradient of moisture is quite high. This moisture discontinuity line is a soft spot for thunderstorms formation. In some cases, this zone of moisture gradient may have a slope (with height) towards the moist air, when the first outbreak may be spread out over a larger area.

5.6.4 Even the surface dew point temperatures give an idea of the degree of moisture. Hence, large changes in dew point temperatures will provide some

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* I.Met.D. Tech. Note No.10(1944) on Nor'westers of Bengal, contains a discussion based on special meteorograph ascents made at a number of stations in and around West Bengal; in Fig.4 and 5 of this Tech. Note, the tongue of moisture in the upper air has been clearly brought out.

useful information in nor'wester forecasts. As an illustration of the usefulness of even the surface humidity values, an analysis of the surface relative humidity at 0300Z at Asansol and the subsequent thunderstorm activity (over Gangetic West Bengal and Bihar Plateau) is given in the following table (Table III).

TABLE – III

Statistics of thunderstorm activity over Gangetic West Bengal and Bihar Plateau in relation to 0300Z Relative Humidity at Asansol on the same day.

(Period of data – April and May 1964-1973)

Relative humidity % at 0300Z at Asansol	Total No. of days	% frequency of days of thunderstorm activity			
		Dry	Isolated	Scattered	Fairly widespread/ Widespread
< 50%	192	86	8	6	–
51-70%	241	48	27	19	6
71-80%	90	35	24	25	16
>80%	30	13	30	37	20

The table very clearly brings out the increase in thunderstorm activity as the moisture supply increases.

5.6.5 The vertical distribution of moisture is provided by radiosonde ascents. It determines the degree of instability and whether it can be realised. From a consideration of upper air flow pattern alone we cannot decide whether an air stream is moist or dry. The wind flow will have to be studied along with the radiosonde data to determine moist and dry air streams and their advection.

5.7 Synoptic situations

5.7.1 Although thunderstorm is a meso-scale phenomenon, the realization of the instability is largely dependent upon the large scale synoptic situation – particularly the vorticity of motion in free atmosphere. Petterssen has given statistics to show that deep convection is mostly associated with cyclonic vorticity (at 750 mb level), while anticyclonic vorticity has a preference for shallow convection. Though Petterssen's data refer to middle latitudes, his conclusions appear to be applicable to the tropics also as will be evident from the studies of thunderstorms in association with different synoptic situations, made in our country. Significant thunderstorm activity is generally associated with some synoptic system or other of the cylonic type. However, many of these systems are generally weak. This necessitates a careful analysis of the charts, great need to maintain space and time continuity in the analysis and also the need for the forecaster to be well aware of the diurnal variations and local peculiarities of the area.

5.7.2 Surface and lower tropospheric features

5.7.2.1 During the pre-monsoon months, particularly April and May, Bihar Plateau and the adjoining areas is under the influence of a low pressure system (usually an extended trough), which may become more intense during the afternoon. Trough lines (or wind discontinuities) may extend from Bihar Plateau southwards to southeast Madhya Pradesh and also eastwards to Assam – Meghalaya. This general trough is a region favourable for development of lows. When the seasonal high over the Bay of Bengal is also well-marked and is situated over north and the adjoining central Bay, the southerlies to the east of the low pressure system over Bihar Plateau, become strong leading to a well-marked inflow of moisture from the Bay into Gangetic West Bengal and adjoining areas.

5.7.2.2 The common synoptic situation in the surface and the lower troposphere, favourable for the intensification of the trough over Bihar Plateau and adjoining areas leading to good nor'wester activity in northeast India, is the movement of western disturbances and induced lows across northwest India, Uttar Pradesh and north Madhya Pradesh. In a typical case,

i) the induced low is over Punjab-Haryana, Rajasthan, West Uttar Pradesh or northwest Madhya Pradesh

ii) a trough extends eastsoutheastwards from the low to Bihar Plateau, and

iii) easterlies penetrate westwards over Bihar Plains and Uttar Pradesh upto 1.0 or 1.5 km.

5.7.2.3 The presence of these easterlies over Bihar Plains and Uttar Pradesh is in contrast to the seasonal westerly flow over these sub-divisions. Either the induced low itself moves east or southeastwards along the trough or fresh cyclonic circulations develop along the trough. Even though the low may be over northwest Madhya Pradesh or southwest Uttar Pradesh on the morning charts, it usually moves rapidly to Bihar Plateau, East Madhya Pradesh or Orissa by the afternoon/evening and gives rise to good thunderstorm activity in northeast India. Next morning, the low may again shift westwards, only to come back again to Bihar Plateau area by the evening. This process may repeat for 2 or 3 days till the induced low moves away eastwards or becomes unimportant. Thus, the forecaster has to be on the alert for development of thunderstorms in northeast India even when the induced low is over Northwest Madhya Pradesh or West Uttar Pradesh.

5.7.2.4 The location of the east-west trough line east of 80°E, associated with the low further west, determines the area of thunderstorm activity over northeast India. This trough may be anywhere from north Uttar Pradesh and north Bihar in the north to southeast Madhya Pradesh and south Orissa in the south, depending upon the position of the induced low. The induced low may be seen either as a closed cyclonic circulation or only as a trough. These systems may also get linked up with the seasonal discontinuity further south over the Peninsula. The diurnal eastward or southeastwards shift of the induced low discussed above is more pronounced when the western disturbance and the induced low are weak.

5.7.2.5 The movement of the induced low becomes erratic when it reaches northeast India, except when it is well-marked. Areas of cyclonic turning in the isobaric configuration or wind flow associated with the low/trough, are more favourable for thunderstorm activity than an anticyclonically turning pattern. The necessity of cyclonic turning is implied in the method of predicting nor'westers over Gangetic West Bengal based on the pressure differences between Calcutta, Barisal and Berhampur (Ref. para 1.7 of I.Met.D. Tech. Note No.1).

5.7.2.6 Another important feature which causes low level lifting is the cold downdraft from the parent thunderstorm which triggers off more thunderstorms downstream. Such a mechanism can produce a chain of thunderstorms, one following the other.

5.7.2.7 It may also be noted in this connection that the area we are discussing is one where insolation is high. During April and May, the mean temperatures over Bihar, interior Orissa and Gangetic West Bengal and the adjoining East Madhya Pradesh are quite high - of the order of 31°C to 34°C. The high temperature is an effective source of low level heating leading to the realisation of the instability.

5.7.3 Mid- and Upper Troposphere

5.7.3.1 In the mid- and upper troposphere, the flow over northeast India in this season is mainly westerly. Perturbations in the westerlies can be either a trough or a jet stream or a cut-off' low. Towards May, the westerlies weaken and the jet stream disappears from northeast India. A deep westerly trough is a very powerful mechanism in causing widespread thunderstorms over northeast India (a typical case in the second fortnight of April 1971 is discussed in Section 16). Sometimes, the trough may develop large amplitude only after entering India. For the season as a whole, the jet stream is a more common feature over northeast India than a westerly trough and a jet is associated with more number of occasions of thunderstorms over Gangetic West Bengal, Bihar and Orissa than a westerly trough. With the improved network of rawin observations now, it should be possible to locate the jet stream fairly objectively on the daily charts and maintain day-to-day continuity.

5.7.3.2 The superposition of favourable surface and upper air conditions will result in generally widespread nor'wester activity. It is well known that in typical cases of troughs "appreciable amounts of vorticity advection aloft are limited to small areas, separated by vast areas of insignificant amounts". Similar is the case with jet maxima also. As no numerical computations of vorticity are available in operational forecasting work, the forecaster has to qualitatively locate the areas of large vorticity and its advection by a mere inspection of the analysed charts and forecast the areas favourable for thunderstorm development.

5.7.3.3 The advection of warm air in the lower levels and cold air in the upper levels over the area will have to be judged by the isotherm distribution taken together with the air flow at these levels. Thermal winds will have to be taken into account to supplement the radiosonde data while drawing the isotherms. The cold air advection in the upper levels is fairly prominent when there is a well-marked trough to the west, upstream.

5.7.3.4 The above synoptic situations are generally seen in April and the beginning of May. They may be noticed in March also. However, by the middle of May when precedent to the onset of the monsoon over the country, rapid changes begin in the circulation features, the flow patterns change over northeast India also. The main changes are:

i) The anticyclone over the north Bay collapses which leads to some changes in the lower level flow pattern. In the mean, there is a general backing of the low level winds over Gangetic West Bengal and Orissa which may imply more occasions of winds with greater southerly components reaching these areas.

ii) The seasonal low establishes over Rajasthan and Pakistan, with the result that the lows over northeast Madhya Pradesh and south Uttar Pradesh and Bihar State which are associated with the development of thunderstorms over northeast India, become relatively less important and less conspicuous on the charts.

iii) Formation of low pressure systems in the Bay of Bengal becomes more frequent and is also at more northerly latitudes, changing the flow pattern over Gangetic West Bengal and Orissa in the low levels. Winds often change to southeast/east, and there is also a greater flow of moisture into these areas.

iv) The upper westerlies weaken.

As a result of these changes, thunderstorm activity increases in the coastal areas of West Bengal and Orissa in the second half of May. The sequential movement of thunderstorms from west towards east/southeast may not be found and squalls may occur in these areas from south or east also, in contrast to the northwesterly squalls earlier in the season.

5.7.3.5 While the synoptic situations give us the broad areas where conditions are favourable for the occurrence of thunderstorms, it is necessary to take into account other factors such as moisture distribution in the horizontal and the vertical, stability conditions etc. to forecast more precisely the possible areas of outbreak of thunderstorms. A still further refinement in locating the thunderstorm areas can be had for short term forecasting by following the sequence of hourly weather reports, radarscope observations etc.

5.7.3.6 The forecaster has to take into account all the factors discussed in the previous paragraphs and arrive at an integrated judgement. He has to take note not only of the features present on the day's chart but also how they have changed during the preceeding 24 hrs, so that he can judge whether the day's weather will be less or more intense than the weather on the previous day. In order to ensure that all the factors have been taken note of and nothing is missed, it is advantageous to have a check sheet. It is desirable that each F.O. has its own check sheet to suit its special local needs.

6. Thunderstorms in Sub-Himalayan West Bengal and in Assam and adjacent States

6.1 General

6.1.1 Sub-Himalayan West Bengal and Assam and adjacent states is a region of high frequency of thunderstorm activity during the pre-monsoon season. In some respects, the thunderstorms over this area (except Tripura and Manipur) are different from the nor'westers of Gangetic West Bengal discussed in the previous section. One of the main differences is the predominance of thunderstorms during night and early morning hours. Over 70% of thunderstorms in Arunachal Pradesh, Assam and Meghalaya occur during night time. At Gauhati 50% of the thunderstorms occur between 1800 and 2400 hrs IST In contrast, Tripura, Manipur and adjacent areas have a thunderstorm frequency maximum in the afternoon/evening as in Gangetic West Bengal.

6.1.2 The thunderstorms in Sub-Himalayan West Bengal, Assam and adjacent states have been classified as Type B thunderstorms in India Met. Department Tech. Note No.10, and they were shown to be usually moving southwards. But east-west moving thunderstorms are also not infrequent. Thunderstorms which develop in West Bengal in the afternoon/evening move into Assam and adjacent states during the night. Movement of thunderstorm cells have been traced west-east from Bagdogra to Mohanbari as well as north-south from Dhubri to Barisal.

6.2 Typical Radiosonde Ascents

6.2.1 The typical tephigrams of Calcutta (in the pre-monsoon season) have been discussed in para 5.5. The tephigrams of Gauhati differ in many respects from those of Calcutta. The lower troposphere over Gauhati is colder than Calcutta and the air is also more moist. The temperatures as well as the virtual temperatures are colder at Gauhati than at Calcutta by 4°C to 5°C. The inversion and the rapid decrease of moisture with height in the low levels, characteristics of the curves at Calcutta, are not usually present at Gauhati; at any rate it is not so prominent. To this extent, convection is not inhibited over Assam so strongly as in Gangetic West Bengal.

6.2.2 The mean tephigrams of Gauhati for thunderstorm and non-thunderstorm days during April and May in Assam, Meghalaya and Arunachal Pradesh are given in Figs. 6.1 a and 6.1 b respectively. As thunderstorms in the above area occur mostly during night time, the 1200Z radiosonde ascent will be more representative of the atmospheric conditions and hence the mean tephigrams were based on 1200Z data. The main features brought out by the mean tephigrams are:

i) The air is fairly moist upto about 700 mb on thunderstorm days

ii) Compared to non-thunderstorm days, there is a good increase of moisture on thunderstorm days in the lower troposphere (the moisture content is more in May than in April).

iii) The upper troposphere is warmer on thunderstorm days. Below 500 mb there is not much difference in dry bulb temperatures between a thunderstorm and a non-thunderstorm day.

iv) There is also no large difference in lapse rates between thunderstorm and non-thunderstorm days; if at all, the instability is slightly less on thunderstorm days.

v) The atmosphere is conditionally as well as convectively unstable on all the days; but it is only on thunderstorm days, that the instability is realised, one of the reasons being the higher moisture content. On non-thunderstorm days, lack of suitable trigger action as well as the greater dryness of air leading to the erosion of the clouds due to entrainment leads to the non-realization of the instability present in the atmosphere.

6.3 Moisture

6.3.1 Since the mean tephigrams of Gauhati shows that the moisture content, rather than the lapse rate, is the more significant difference between a thunderstorm and a non-thunderstorm day, an analysis of the dew points in the lower troposphere was made. The dew point at 850 mb of the ascent (00Z or 12Z) preceding the thunderstorm occurrence was taken as representative of the lower level moisture. The results of the analysis are shown in Table IV.

TABLE - IV

Frequency of occasions of thunderstorm/non-thunderstorm days in Assam and Arunachal Pradesh associated with different ranges of T_dT_d values at 850 mb level over Gauhati

[Based on data of April and May (1-15th)]

(1968-70 and 1972-73)

Range of T_dT_d (°A)	No. of Observations	No. of days			
		Dry	Isolated thunderstorms	Scattered thunderstorms	Widespread thunderstorms
<281	3	2(67)		1(33)	-
281-283	67	18(27)	26(39)	14(21)	9((13)
284-286	139	18(13)	52(37)	41(30)	28(20)
>286	179	5(3)	50(28)	59(33)	65(36)

(Figures in brackets give % frequency)

The table brings out clearly the importance of moisture and the increase in thunderstorm activity with the increase in moisture. So far as Gauhati is concerned, a Td Td value of 284°A at 850 mb appears to be critical. Below this value on a larger number of occasions, weather is either dry or only isolated thunderstorms occur; above the critical value, conditions become more favourable for thunderstorm activity. But low level moisture is only one of the favourable features for convective activity; unless other factors are also favourable thunderstorms may not occur.

6.4 Synoptic situations

6.4.1 Surface and lower tropospheric levels

6.4.1.1 The low level synoptic conditions favourable for thunderstorm activity are:

i) A low pressure area or a trough of low pressure over Bihar, West Bengal and Bangla Desh is a favourable synoptic situation. The low may be better noticed as a cyclonic circulation in the lower levels than on the surface chart. However, it must be noted that no regular sequence of a moving low can be traced over West Bengal, Assam and adjacent states, except when the system is well-marked. Large diurnal variations mask the synoptic features.

ii) A well-marked east-west oriented discontinuity between easterlies over sub-Himalayan West Bengal and Assam and southerlies or southwesterlies to the south is another favourable situation. The discontinuity may be noticeable upto 1.0 or 1.5 km. With the east-west discontinuity, the thunderstorms are mainly in the area of the easterly current (for a situation of this type, see Fig. 6.2). The easterlies being colder, (vide para 6.2.1) a mechanism of the warmer southerlies rising over the colder easterlies and giving rise to weather looks plausible. Although a density discontinuity is present along the east-west discontinuity line, the pronounced dew-point discontinuity noticed over Bihar and Gangetic West Bengal is not noticeable over Assam and adjacent states.

iii) One of the low level synoptic features causing thunderstorms is said to be the 'low level' jet. The winds over Gangetic West Bengal and Bangla Desh are often strong southerlies, with speeds reaching 35-40 kts, particularly during night time as shown by the 1800Z ascents. The downstream weakening of the strong southerlies as they reach further north, may cause low level convergence. This may be one of the causes for the night time thunderstorms in Sub-Himalayan West Bengal and Assam and adjacent States (see Fig. 6.3). Besides when a strong warm moist advection in the low levels is superposed by cold dry advection in the upper levels, instability may set in due to large vertical variations in advection. In USA it has been shown that such regions are favourable for tornado outbreaks.

6.4.2 Mid- and Upper Troposphere

6.4.2.1 The flow over sub-Himalayan West Bengal, Assam and adjacent states is one of westerlies in the mid- and upper troposphere. These westerlies which cover most of the northern India in the pre-monsoon season form part of the westerly flow over the middle latitudes. The types of perturbations in the westerly field are

i) eastward moving trough and

ii) jet stream

These perturbations affect the weather over north India in general.

6.4.2.2 An examination of the past few years charts shows that a large majority of spells of thunderstorm activity in sub-Himalayan West Bengal and Assam and adjacent states is associated with the passage of troughs in westerlies. In many cases, the trough is to the north of the country and only the extreme southern end affects sub-Himalayan West Bengal and Assam and adjacent states. Sometimes the trough may extend further south. On rate occasions, the trough extends as far south as Madhya Pradesh and Orissa. When only the extreme southern tip of the trough extends into northeast India, the wind changes at stations in Assam and sub-Himalayan West Bengal may not always clearly reveal the passage of the trough. In such cases, the rawin stations in east Tibet may give very useful indications of the approach and passage of the trough. An example of the time section of Lhasa showing the passage of westerly troughs is shown in Fig. 6.4. The corresponding weather over sub-Himalayan West Bengal, Assam and Arunachal Pradesh is also indicated in the figure.

6.4.2.3 In this connection, it may be mentioned that in the mean upper wind charts for the pre-monsoon period, a trough is noticed over West China on the lee side of the Tibetan Plateau, particularly at 700 mb level. As a result of this quasi-stationary trough, it should be expected that when the troughs in westerlies in the mid- and upper troposphere moving across Tibet reach the lee side of the plateau, there may be an amplification of the trough over the area, its extension to the lower levels (viz. 700 mb) or to a slightly more southerly latitude and also perhaps a little slowing down. All these may result in a prolongation and an intensification of the thunderstorm activity in Arunachal Pradesh. In some of these cases, Arunachal Pradesh alone may get thunderstorms without sub-Himalayan West Bengal, Assam and Meghalaya being affected. During the passage of the mid- and upper tropospheric trough, the lower level winds (from 850 mb upwards) over Assam and adjacent states become south/southwest; they are also stronger than normal and get more organized with height.

6.4.2.4 A fair number of these troughs have an embedded jet stream so that the effect of the jet and the trough become additive in certain areas and enhance the thunderstorm activity there.

6.4.2.5 From what has been discussed, it would be clear that for a successful forecasting of thunderstorms in sub-Himalayan West Bengal and Assam and adjacent states, it is very desirable to follow the sequence of synoptic events over Tibet, Sinkiang and West China. A time-section of an extra India station like Lhasa may serve as a key aid in this connection.

6.4.3 Orography

6.4.3.1 Another important factor in sub-Himalayan West Bengal and Assam and adjacent states is orography. Orography provides forced lifting of the low level moist air. Again the katabatic flow from the mountains into the valleys during the night time provides under-cutting of the low level warm moist air.

7. Thunderstorms and Duststorms in Northwest India and Uttar Pradesh

7.1. General

7.1.1 Thunderstorms occur in northwest India and West Uttar Pradesh in all the months of the pre-monsoon season. The activity is more in Western Himalayas than in the plains. The activity is also more in the second half of the season than in the first half in the plains.

7.1.2 Duststorms occur only in the plains; the area comprising of Punjab, Haryana, north Rajasthan and the adjoining West Uttar Pradesh has the maximum of duststorm activity. Significant duststorm activity begins only in April. It extends into June also. In fact, June is the month of maximum duststorm activity. These dust-storms are locally known as "Andhi".

7.1.3 Duststorm is of two types, depending upon the mechanism of the occurrence. They are:-

i) pressure gradient type and

ii)convective type

Pressure gradient type duststorms occur due to strong winds raising loose dust. It is not associated with any Cb development. In the convective type, dust is raised by the downdraft from the Cb cloud. Duststorm often proceeds a thunderstorm. Pressure gradient type duststorm will be discussed in a subsequent section (Section 10) under dust-raising winds. The duststorms referred to in this section are mainly of the convective type.

7.2 Typical Radiosonde Ascents

7.2.1 During the pre-monsoon season, atmosphere over northwest India, Uttar Pradesh and the adjoining areas is very dry with nearly dry adiabatic lapse rates. Quite often, radiosonde stations in these areas (such as New Delhi) report motorboating, because of very low humidity. In spite of the high instability, no convective clouds form due to lack of moisture. On days of thunderstorm, there is an incursion of moisture at all the levels, being quite considerable in the lower troposphere. On some days, it is noticed that the incursion is large in the middle troposphere. Mean tephigrams of Delhi for days of scattered or widespread thunderstorms or duststorms and no thunderstorm (or duststorm) within 250 km of the station are given in Fig. 7.1. Two curves are given for thunderstorm days -

i) 00Z curve when thunderstorm/duststorm occurred before 12Z of the day.

ii) 12Z curve when thunderstorm/duststorm occurred after 12Z of the day. The curve for non-thunderstorm days refer to 00Z.

The main differences between a thunderstorm and a non-thunderstorm day are:-

i) There is not much difference either in the temperatures or in the lapse rates upto 400 mb, between thunderstorm and non-thunderstorm days. Above this level, the air is warmer on thunderstorm days than on non-thunderstorm days.

ii) The moisture content is more on thunderstorm days over the entire atmosphere, the increase in moisture being considerable in the lower troposphere On some individual occasions, large incursion of moisture in the mid-tropospheric levels has also been noticed.

7.2.2 If we take the 850 mb dew point temperature as representative of the low level moisture content, the analysis given in Table V shows that over 90% of days of Td Td values less than 277°A are without thunderstorms. When Td Td is greater than 277°A, the chances of thunderstorms increase considerably. 1200Z Td Td values seem to give better indications of occurrence of thunderstorm.

TABLE - V

Statistics of Td Td values at 850 mb level over New Delhi in relation to thunderstorm activity over New Delhi and surrounding area (250 km radius)

(Period of data: 1968–1973 - April and May)

(i) 00Z Observations				(ii) 12Z Observations			
Range of Td Td (°A)	No. of occa-sions	Non-thunder-storm days	Days of scat-tered to wide-spread thunder-storms or dust-storms (occur-ring between 00Z and 12Z)	Range of Td Td (°A)	No. of cca sions	Non-thunder-storm days	Days of scat-tered to wide-spread thunder-storms or dust-storms (occur-ring after 12Z)
<270	8	8(100)	0(0)	<270	3	3(100)	0(0)
270–273	26	25(96)	1(4)	270–273	25	23(92)	2(8)
274–277	36	32(89)	4(11)	274–277	30	27(90)	3(10)
278–281	25	18(72)	7(28)	278–281	27	16(59)	11(41)
282–285	8	4(50)	4(50)	282–285	12	2(17)	10(83)
>285	5	2(40)	3(60)	>285	12	0(0)	12(100)

7.2.3 An analysis of the Total Totals Index [refer para 5.4.1(c)] of New Delhi for the period 1968–73 with reference to thunderstorm activity within 250 km of the station was also made and the results are given in Table VI. The critical value of Total Totals Index was seen to be 48°(A) above which the likelihood of thunderstorm increases. When we examine the Cross Total and he Vertical Total (which together make up the Total Totals), it was found that only the Cross Total plays a significant part, while the Vertical Total is indifferent . This again brings out the greater importance of moisture content in the production of thunderstorms.

TABLE - VI

Statistics of Total Totals Index of New Delhi associated with thunderstorm and non-thunderstorm days

(Based on data 00 and 12 GMT of April and May 1968-1973)

	Total No. of occasions	TTI $< 48°$	TTI $\geq 48°$
No. of days of scattered to wide-spread thunderstorm or duststorm	57	9	48
No. of days of no thunderstorm or duststorm	160	109	51

7.2.4 The deficiency of moisture in the atmosphere is often adduced as the reason for the occurrence of a duststorm rather than a thunderstorm. However, it has been shown (Bhalotra, 1954) that there is no difference in the atmospheric humidity content between a day of duststorm and a day of thunderstorm.

7.3 Synoptic situations

7.3.1 Surface and lower troposphere

7.3.1.1 Northwest India, Uttar Pradesh and the adjoining north Madhya Pracesh is a region of a rather weak pressure field particularly in the earlier half of the season. By May, the heat low shifts to Rajasthan and moderate to strong pressure gradient builds up over Gujarat, south Rajasthan and the adjoining Madhya Pradesh. The heat low is very shallow and is confined only to the surface chart. In the mean seasonal flow, no cyclonic circulations can be noticed in the low levels.

7.3.1.2 Synoptic disturbances that affect this area during the pre-monsoon season are the western disturbances and their associated induced lows. An examination of the past charts indicates practically all the spells of convective activity in northwest India, West Uttar Pradesh and the adjoining areas are associated with a western disturbance or its associated induced lows over Pakistan, Northwest India and the adjoining areas. The cyclonic circulation associated with an induced low may extend upto 1.0 or 1.5 km. The western disturbances and the induced lows may be seen either as a closed low or only as a trough.

7.3.1.3 In the low levels, a trough may extend eastwards or southeastwards from the induced low and the trough region is a potent field for thunderstorm activity. In association with the western disturbances and induced lows, easterlies/southeasterlies often prevail over Uttar Pradesh and northern parts of northwest India in the low levels (say upto 1.0 or 1.5 km); thunderstorms and duststorms are mostly in the region of the trough line and the easterlies to the north. Orography enhances the convective activity over Western Himalayas.

7.3.2 Mid- and Upper Troposphere

7.3.2.1 Troughs in westerlies and jet streams move across northwest India and Uttar Pradesh in the mid- and upper troposphere during this season. Simultaneous with the passage of western disturbances and induced lows at the surface and in the lower troposphere over northwest India and Uttar Pradesh, troughs in westerlies and jet streams may also be seen in the mid- and upper troposphere. Both of them (trough and jet stream) or only one of them may be present. Since western disturbances and upper air troughs are better developed and more frequent in the more northern latitudes, convective weather is also more in the northern part of northwest India (roughly north of 30°N) than further south.

7.3.2.2 The time-sections of Jodhpur, Delhi, Lucknow and Srinagar are very useful to trace the movement of troughs and jet maxima in the westerlies. Some of the special features of the troughs over this region are:-

i) They may occasionally develop large amplitude over the Indian region

ii) A retrograde motion may be noticed sometimes; but the retrograde motion is only apparent. On such occasions, it is seen that the apparent retrograde motion has been due to the formation of a new shortwave trough upstream.

iii) Some of the short wave troughs are only of small longitudinal extent, so that careful analysis taking into account all significant changes in the observations, coupled with space and time continuity is required to locate these trough systems. The analysis should also extend to the middle latitudes in the north, since quite often what we notice over the Indian latitudes is only the southernmost end of the trough moving across more northerly latitudes.

iv) When a blocking high is present to the north of India, the troughs in westerlies may move along more southerly latitudes, to the south of the blocking high and extend well into the Indian latitudes, almost upto Madhya Pradesh and north Peninsula.

8. Thunderstorms over the central parts of the country (Madhya Pradesh and Vidarbha)

8.1 General

8.1.1 East Madhya Pradesh and the adjoining areas is another region of high thunderstorm activity during the pre-monsoon months. It is one of the four major areas of thunderstorm activity over the country in this season – the other three being northeast India, southwest Peninsula and the extreme northern parts of the country. The activity commences over Madhya Pradesh and Vidharba even by March; but it increases considerably in April and is maintained in May also. The activity is comparatively less in the western districts of West Madhya Pradesh. While the mean monthly number of thunderstorm days is as high as 10–12 days in southeast Madhya Pradesh in April and May, it is only about 4 days in the western districts of West Madhya Pradesh. The northern parts of Madhya Pradesh get duststorms also.

8.1.2 During the pre-monsoon season, a wind discontinuity oriented southwest-northeast across east Vidharba and southeast Madhya Pradesh, is a normal feature of the wind circulation in the low levels. In March and April the winds to the south and east of the discontinuity line are generally south/

southwesterly skirting around the anticyclone over the Bay, while on the northern and western sides, the winds are northwesterlies/northerlies. The discontinuity is usually seen upto about 1.0 km; and it is also one of moisture discontinuity, since the southerlies/southwesterlies are comparatively moist while the northwesterlies/northerlies are dry. This discontinuity line is a potential region for thunderstorm development; and aided by afternoon insolation and orography, isolated convective development takes place along this line in southeast Madhya Pradesh on most days (Fig. 8.1). But large scale convection over Madhya Pradesh and Vidarbha occurs only with definite synoptic situations.

8.1.3 The orography of Madhya Pradesh and Vidarbha plays a great role in the development of thunderstorms. The first thunderstorms invariably occur in the areas with an elevation of 0.5 km or more asl. Pachmarhi and neighbouring areas (Mahadeo hills), where the elevation is highest in the region, are very favourable spots for thunderstorm development. This place also appears to generate thunderstorm of destructive character.

8.1.4 The thunderstorms in Madhya Pradesh and Vidarbha are accompanied by squalls on nearly 50% of the occasions. At Nagpur, for instance, while the common peak velocity in a thundersquall is about 50-80 kmph, squalls exceeding 120 km/hr. have also occurred. In view of the lack of sufficient moisture, thunderstorms in West Madhya Pradesh may not be accompanied by significant precipitation on many occasions.

8.2 Synoptic Situations

8.2.1 Large scale convective activity over Madhya Pradesh and Vidarbha is usually associated with recognizable synoptic systems on the charts. These systems will be discussed now.

8.2.2 Surface and Lower Troposphere

8.2.2.1 The synoptic systems seen on the surface and lower troposphere on days of thunderstorm may be one of the following:-

i) systems in westerlies viz. western disturbances and induced lows

ii) systems in easterlies and

iii) low pressure systems which develop locally.

The systems in westerlies are more common than the other two types.

(i) Systems in Westerlies:

A western disturbance or an induced low over Rajasthan is a favourable synoptic situation. The induced low may move east or even southeastwards to south Uttar Pradesh and north Madhya Pradesh. In typical cases, when the induced low is present over Rajasthan, a trough may extend south/southeast to Madhya Pradesh. The induced low and the trough extending southwards from it may be seen on the surface and in the lower tropospheric levels upto 1.0 km or 1.5 km. A cyclonic circulation may also develop in this trough. Thunderstorms are usually confined to the north and east of the trough line in the field of southeasterlies/southerlies while to the west of the trough where the winds are generally northwesterly/northerly, there is no thunderstorm, except close to the trough line. Towards the second half of period when low pressure systems develop in the Bay, the trough over Madhya Pradesh may extend further southeastwards into West Central Bay across Andhra Pradesh and link up with the low pressure system over West Central Bay. Under such conditions, there could be a large influx of moisture into East Madhya Pradesh and Vidarbha from the Bay which may result in widespread and severe convective activity. In all these cases, weather may be mainly in northwest and East Madhya Pradesh and Vidarbha; southwest Madhya Pradesh may not get much weather.

(ii) Systems in Easterlies:

Under the influence of low pressure systems moving westwards across the Peninsula or which are over the Southeast or East Central Arabian Sea, a trough line may extend northwards into Vidarbha and East Madhya Pradesh. In such cases, Vidarbha and the adjoining south Madhya Pradesh may get weather, while further north there may be no thunderstorms. Even in Vidarbha and the adjoining south Madhya Pradesh, thunderstorm activity may be only isolated or scattered with light rain. However, when an induced low is also simultaneously present over north Madhya Pradesh, south Rajasthan or south Uttar Pradesh, the combined influence of the systems in the westerlies and in the easterlies may result in large scale thunderstorm activity over the central parts of the country.

(iii) Sometimes low pressure areas or cyclonic circulations may develop in situ over north Maharashtra State or adjoining Madhya Pradesh and cause weather over the central parts of the country.

8.2.3 Mid and Upper Troposphere

8.2.3.1 The mid- and upper tropospheric flow patterns associated with thunderstorm activity over the central parts of the country are

a) trough in westerlies

b) jet stream and

c) anticyclonic circulation.

They will be described below:-

(a) A deep trough in westerlies extending upto Madhya Pradesh is seen on some occasions of thunderstorms. But such occasions are only a few. Even without any well-marked trough immediately to the west, large scale thunderstorm activity may take place over Madhya Pradesh and Vidarbha when the winds there are strong southwesterlies. This may imply a trough further west over the Arabian Sea, but it is difficult to locate the trough due to lack of data.

(b) On some occasions, particularly in March and April, the westerly jet may move far southwards from its mean seasonal position and may lie over Madhya Pradesh and Vidarbha.

(c) Towards the end of the season when the upper westerlies weaken and shift northwards, an anticyclone may lie over Madhya Pradesh.

8.2.3.2 Either one or more of these upper air flow patterns are noticed on occasions of large-scale thunderstorm activity over the central parts of the country.

8.3 Radiosonde Ascents

8.3.1 Nagpur is the only radiosonde station in this area. In a study of thunderstorms at Nagpur (India Met. Department, Scientific Report No.41) it has been shown that an increase in moisture in the lower troposphere is necessary. The mean Td Td values at the various standard levels from surface to 700 mb on days of thunderstorms (in general) and severe thunderstorms at Nagpur, as given in that study, are reproduced below:-

	Mean Td Td (°C) for thunderstorms(in general)				Mean Td Td (°C) for severe thunderstorms			
	Mar.	Apr.	May	June	Mar.	Apr.	May	June
Surface	13.0	15.8	17.3	21.8	16.3	20.4	21.8	21.8
900 mb	9.7	9.2	14.2	16.9	12.8	13.6	17.8	17.8
850 mb	6.6	7.5	11.7	15.3	9.0	11.9	15.9	16.7
800 mb	5.0	5.7	9.0	13.0	5.3	8.7	12.2	15.8
700 mb	-2.7	1.4	3.9	6.9	-1.7	2.8	6.5	11.2

9. Thunderstorms in Peninsula

9.1 General

9.1.1 The southwestern part of the Indian Peninsula consisting of Kerala and the western parts of Tamil Nadu and Mysore is another region of high thunderstorm activity in the pre-monsoon season. Over Kerala, the activity is maximum. Thunderstorm activity over southwest Peninsula is mainly in Arpil and May, although even by March thunderstorms commence in the southern parts of Kerala. In a general way, the activity is somewhat more in May than April. In April and May, thunderstorms occur in Kerala for nearly 15 days in each month, nearly as much as in Assam and adjacent states. Orography coupled with the plentiful supply of moisture from the sea and the effect of sea breeze are quoted as some of the causes for the high thunderstorm activity in southwest Peninsula. In contrast, the east coast of south Peninsula has very much less of thunderstorms.

9.2 Synoptic situations

9.2.1 During this season (particularly in March–April), a wind discontinuity in the lower troposphere (upto 1.0 km) extending from south Kerala to East Vidarbha and southeast Madhya Pradesh is a seasonal feature. This seasonal wind discontinuity often shows some east–west oscillations. In the extreme cases it may be close to the east coast of the Peninsula or along the west coast. Sometimes when a trough of low is present over southeast Arabian Sea, the seasonal wind discontinuity may run from southeast Arabian Sea northeastwards to Vidarbha. The seasonal wind discontinuity is also a line of moisture discontinuity. The air to the south and east is generally moist while the air to the west is much drier particularly in the north peninsula. Aided by orography and afternoon insolation isolated thunderstorm activity may occur along this discontinuity on most of the days.

9.2.2 Thunderstorms over the Peninsula in this season are afternoon/evening phenomena occurring usually between 15 and 21 hrs IST. Sometimes they may occur later in the night also. But early morning hours and day time till 1500 hrs IST are free from thunderstorm, unless there is a migratory cyclonic disturbance such as a low pressure area, depression or a cyolonic storm.

9.2.3 On some days, thunderstorm activity may increase and become even fairly widespread over portions of the Peninsula. It is found that such occasions are characterised by one or more of the following synoptic situations:–

i) The seasonal north–south wind discontinuity may become well–marked with one or more cyclonic circulations embedded in it. A favourable synoptic situation for the seasonal wind discontinuity to become well–marked is when an induced low forms over the central parts of the country. On such occasions the seasonal wind discontinuity gets linked up with the induced low.

ii) Troughs in mid- and upper tropospheric westerlies sometime amplify and extend southwards into the central parts of the country and north Peninsula. Very occasionally the trough may extend further south even into south Peninsula and the upper westerly regime may oover the whole country. The upper trough along with the low level wind discontinuity gives rise to large scale thunderstorms over the Peninsula. Over the south Peninsula, the upper northerlies in the rear of the trough can cause an advection of positive vorticity on account of the decrease of Coriolis parameter down-stream, leading to thunderstorm development.

iii) When the regime of the upper westerlies extends to more southern latitudes, we notice, on a number of occasions, the lower tropospheric seasonal wind discontinuity is also well-marked and thunderstorm activity increases over the Peninsula. Sometimes a jet maximum may also be noticed in the strong westerlies over the Peninsula. The extension of the regime of westerlies southwards is mostly in March and April. It becomes less and less frequent as the season advances and is rare in May.

iv) Another type of disturbance that produces large scale thunderstorm activity over the Peninsula is the system in easterlies. This is usually noticed when the easterly flow is well-marked over the Peninsula, south Bay and south Arabian Sea and is sufficiently deep (atleast about 3 kms or so). Often it may not be possible to trace a sequence of movement of such easterly systems. These disturbances may move across the extreme southern parts of the country and Sri Lanka. A favourable place for the low/cyclonic circulation is over Sri Lanka, Comorin and Lakshadweep-Maldives region, when it may get linked up with the seasonal trough/wind discontinuity over the Peninsula. Under such a synoptic situation, widespread thunderstorm activity may occur over south Peninsula with considerable amount of rainfall. The sequential movement of the systems in easterlies could be traced sometimes with the help of satellite cloud pictures. The disturbances in the easterlies may be seen in the lower troposphere in March and

April. But later in the season (i.e. in May), when westerlies prevail over south Peninsula and the adjoining sea areas in the lower troposphere, disturbances in the easterlies may be seen only in the mid- and upper troposphere. Disturbances of more intense nature such as a depression or cyclonic storm also affect the Peninsula during this season. The precipitation associated with them is also accompanied by thunder. These have been already discussed in FMU Rep. No. III-2.1.

v) An east-west oriented shear line in the upper troposphere (300-200 mb levels) across the Peninsula (similar to the one over the west Atlantic discussed by Riehl in his "Tropical Meteorology" - Chapter 10) appears to be another feature causing large scale thunderstorms over the south Peninsula. However, this type of situation is a very rare one. A combination of two or more of the above mentioned synoptic patterns(i) to (v) may sometime take place giving rise to well-marked thunderstorm activity over the Peninsula.

vi) In addition to the above synoptic situations which contribute to the thunderstorm activity over the Peninsula, good thundershower activity is also associated with the onset and advance of the southwest monsoon. Along and near the advancing edge of monsoon current, there is good thunderstorm activity, which continues for a few days - for about a week or so - in the meteorological sub-divisions affected by the advancing edge of the monsoon. This aspect of weather has already been dealt with in some of the earlier FMU Reports - such as "Synoptic features associated with the onset of southwest monsoon over Kerala" (FMU Rep. No. IV-18.2) and "Low pressure areas, depressions and cyclonic storms in the Indian sea areas during pre-monsoon season" (FMU Rep. No. III-2.1). It is also referred to in the different FMU Reports dealing with the typical synoptic situations during the southwest monsoon. Hence, it will not be repeated again in the present report.

10. Dust Raising Winds

10.1 Dust-raising winds occur in the plains of northwest India in the hot weather season. Rajasthan, in particular, experiences dust-raising winds more frequently than the other sub-divisions. Dust-raising winds occur when the pressure gradient is strong. When these winds are sufficiently strong such that the raised dust reduces the visibility below 1.0 km, the phenomenon is called "pressure gradient type dust-storm". Usually when there is a well-marked low pressure area over northwest India, the pressure gradient is strong to the south of the low where the isobars are oriented east-west. This type of lows has usually a large pressure defect from normal. On such occasions, the upper winds in the very low levels (upto 1.5 km) are also very strong – usually of the order of thirty knots, and sometimes reaching as much as 50 kts.

10.2 When the pressure gradient is 1 to 1.5 mb* or more per degree latitude and/or the lowest level upper winds are of the order of 30 kts or more, strong dust-raising winds may be expected over the area. While duststorms of the convective type have a duration of only a few minutes or a fraction of an hour, dust-raising winds last for a long time. Dust-raising winds may commence even in the morning and continue for the whole day. Their intensity reaches a maximum during afternoon/evening at the time of the maximum temperature epoch when the super-adiabatic lapse rates close to the ground favour the raising of the dust. Even after the dust-raising winds/dust-stormssubside, the raised dust remains suspended in the air for a long time, even as much as a few days and reduce the visibility. The raised dust may go up vertically to large heights of a few kms (2 to 3 km) in convective type dust-storms.

10.3 A typical day's synoptic charts with widespread dust-raising winds

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* According to the Departmental convention a pressure gradient of 1 to 1.5 mb per degree is called "Steep pressure gradient" and $>$ 1.5 mb per degree is "Very steep pressure gradient". A gradient of 1 mb per degree at a mean lat. of 25°N (corresponding to Rajasthan) will be equal to a geostrophic wind of 28 kts.

in Rajasthan and adjoining areas are given in Fig. 10.1.

11. Hailstorms

11.1 Hail is precipitation in the form of small balls or pieces of ice with diameter ranging from 5 to 50 mm or even more. Hailstorms cause damage by their impact when they hit. Hailstorms are always associated with Cb clouds.

11.2 In India, hailstorms occur in the northern and central parts of the country; hailstorms are much less common in the Peninsula, and they are confined mainly to

i) interior Maharashtra State

ii) western districts of Interior Karnataka and

iii) Nilgiris and the adjoining ghats areas of Tamil Nadu.

Areas of high incidence of hail storms in the country are

i) along and near Western Himalayas

ii) Assam and adjacent states

iii) West Bengal

iv) Bihar Plateau and

v) East Madhya Pradesh

These are also areas of high thunderstorm frequency, but the number of hailstorms is one to two orders of magnitude less than the number of thunderstorms.

11.3 Hailstorms are common in winter and the pre-monsoon months; occasionally they may occur in north and central India in the post-monsoon months also. But the monsoon period is free from hailstorms. While hailstorms are more in the winter months over northwest India, Uttar Pradesh and Madhya Pradesh, they are more in the pre-monsoon months in northeast India, Peninsula, Vidarbha and the adjoining Madhya Pradesh.

11.4 Hailstorms are associated with Cb development. However, every Cb does not produce hail. The general atmospheric conditions under which hailstorms occur are as follows:-

i) High instability, with Cb clouds growing to very high levels. In radar studies of hailstorms in the U.S., a definite trend of high frequency of hail occurrence was noticed with increased height of the storm echo.

ii) Presence of large vertical currents inside the clouds which will make the hailstones make a number of up and down vertical traverses and also support hailstones of sufficient size before they ultimately fall to the ground. Large vertical currents are again associated with large thermal instability. The hail size is proportional to the updraft velocity in the thunder cloud.

iii) High moisture content in the atmosphere. The greater the moisture content the larger is the size of the hailstones.

iv) Lower freezing level is conducive to hailstorms. One of the factors favourable for hailstorms in north and central India in winter and early spring is the lower freezing levels. In this connection it may be mentioned that in U.S., "studies of hailstorms disclosed that over 90% of reported surface hail occurred where the Wet Bulb Zero* height was between 5000 and 12000 ft. above the terrain. In situations where the larger sizes are reported, the Wet Bulb Zero heights were clustered around an average height of about 9000 ft. above the terrain. Large hails are generally reported with Wet Bulb Zero heights in the range of 7000 to 11000 ft."

v) A preliminary analysis of the upper tropospheric conditions on days of hailstorms shows that the occurrence of hail is generally associated with a strong upper tropospheric southwesterly flow and the jet core coming down to lower altitudes. (A cross-section ~~for mean~~ along Long. 75°E and the 200 mb upper air chart for 0000 GMT of 27 Feb. 1970 are reproduced

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* Wet Bulb Zero is the height where the Wet Bulb Temperature has a value of 0°C. It is assumed that it is an indication of the height of the freezing level within the cloud that may develop over the area.

in Figs. 11.1(a) and (b). Hail was reported from Nagpur Airport and Seoni on this day and from Pachmarhi and Mandla on the next day.

11.5 Hailstone size of 3/4 inch (2 cm) in diameter has been determined as the minimum size to do damage to aircraft.. In the U.S., a nomogram has been prepared to forecast the size of the hailstones reaching the ground; these diagrams are based on certain parameters to be derived from the radiosonde data of the affected area. The hailstone sizes (as derived from the nomogram) have been verified in a few case studies reported in India.

11.6 Apart from the hailstones that reach the ground during the hailstorms, large number of hailstones may be present inside the Cb clouds also, which may be encountered by aircraft-in-flight. Severe hail is one of the phenomena to be included in SIGMET information. Since it is difficult to forecast precisely the occurrence of heavy hail, it is included in SIGMET messages when heavy hail is reported by aircraft or by a ground station or inferred from the radar echoes.

12. Thunderstorm and Radar

12.1 Radar has been extensively used for the study of thunderstorms. It has become an indispensable tool in the detection of thunderstorm cells and their development and to predict their movement. Although the synoptic charts and the radiosonde ascents provide a broadscale picture of the areas favourable for development of thunderstorms, the forecaster has to ultimately depend upon the radar for accurate location of areas where the thunderstorms, squall lines etc. have developed and to prognosticate their movement for short range forecasts for the airfield etc. Radar is particularly very useful to detect tornado cloud development. The characteristic radar picture of a tornado is "the sudden appearance of an appendage from an existing thunderstorm echo which then develops into a 'hook' or 'six shape'" (see Fig. 12.1.).

12.2 There has been considerable work in the last two decades using radar to study thunderstorms. A brief summary of the use of radar for synoptic purposes has been given in WMO Tech. Notes No. 78 entitled "Use of ground based radar in meteorology (excluding upper air measurements)" and No.110 entitled "Use of Weather Radar for Aviation" and in the Departmental publication entitled "Weather Radar Manual (DDGI New Delhi, 1965)".

13. Thunderstorms as seen in Satellite Pictures

13.1 In the satellite pictures, Cb clouds can be easily identified by their high reflectivity, cirriform anvils and the shadows produced. These clouds generally occur in clusters and what is seen in a satellite picture is the merged cirriform top of a number of Cb cells in various stages of development and decay.

13.2 The clusters of Cb clouds associated with severe thunderstorms are seen in satellite pictures as isolated masses of very highly reflective patches of clouds. These cloud masses have usually irregular shapes. When the upper tropospheric winds over the area are strong, the tops of the Cbs may be sheared downwind, so that the downwind portion of the cloud edges (as seen in a satellite picture) are usually feathery while on the upwind side, the cloud edge is sharp and well-defined. The areas surrounding such clusters are clear and the clearance is attributed to strong subsidence. In studies conducted in USA, it has been found that appearance of cells one degree or more in diameter are good predictors of severe weather.

13.3 When a satellite picture of Cb clouds is compared with radar echoes of the same area, the radar echoes form only a fraction of the cloudy area seen in the satellite pictures suggesting that only a small portion of the cloud cluster (seen in the satellite picture) contains active Cb cells.

13.4 Whenever there is an afternoon satellite pass (particularly APT pictures), it may be very useful to locate areas of thunderstorms development, especially if the area is beyond the range of the radar network. Typical afternoon ITOS-1 pass and ESSA-9 pass over India on 19 May 1970 showing the Cb clusters are given in Fig. 13.1. The corresponding 1200Z chart showing the area of thunderstorms is also given for comparison.

14. Some Remarks on the Difficulties in Forecasting Thunderstorms

14.1 In this report, we have presented the synoptic, upper air and aerological conditions favourable for the outbreak of severe convective type of weather. The synoptic charts can only indicate the broadscale severe weather developments; and as such the forecast areas may be considerably larger and the period of validity much longer. The field forecaster using the forecast based on synoptic charts as a guideline delineating the areas where he has to keep a watch for development of thunderstorms, has to depend heavily on reports of actual development of Cb, thunderstorms, linesqualls etc. and their movement, observed by current weather stations, aircraft-in-flight or radar, for purposes of operational point warnings (such as airfield warning etc.).

14.2 The difficulties in prognosticating the development of thunderstorms ~~is~~ are well-known. A successful forecast of severe thunderstorms in the pre-monsoon months depends as much upon the forecaster as on the timely availability of the various observations. The skill and experience of the forecaster, his familiarity with the regional weather, and meticulous attention to details contribute in no small measure to timely forecasts and warnings of thunderstorms. It would be, therefore, be appropriate in this context to quote a few workers in this field, before we conclude the general survey on thunderstorm forecasting and then proceed to the discussions of typical synoptic situations.

(a) "The forecasters use their own skill in predicting the short range movement of the more transitory or sophisticated parameters involved in the specialised severe-weather forecast proceduress. No hard and fast rules for prognosis of these parameters can be devised at this time. Instead, the forecaster must rely on meticulous attention to detail, experience and the ability to anticipate the probable changes in the atmospheric structure. The cardinal principle of severe weather forecasting is to develop a detailed understanding of the current synoptic situation and trend over the past several hours. There is no other way under the present state of art to anticipate the short range changes in the surface and upper air pattern which result in severe-weather outbreaks".

(Col. R.C. Miller - U.S. Air Force, Air Weather Service Technical Report 200 (Rev.), May 1972, p.1-12).

(b) "There is, of course, no standard formula for assigning relative importance to the various factors involved (in forecasting severe thunderstorms) and reliance must be placed on experience in identifying critical conditions".
(S. Petterssen - Weather Analysis and Forecasting Vol.II - Weather and Weather systems (1956) p. 194).

(c) "The forecaster is required to consider dynamic and thermodynamic factors separately in his analysis but he must combine these two when considering forecast requirements. There are occasions when dynamic and thermodynamic factors are strong and well-marked but such situations are not the rule. Most of the time the forecaster is confronted with inconclusive evidence from considerations of dynamic and thermodynamic factors and his judgement and experience become of primary importance".
(Keith A. Browning - AFCRL 65 - 695(1) pp.10-11).

In the following sections we will discuss a few typical synoptic situations.

15. Widespread Nor'wester Activity over Bihar State and West Bengal - 16 to 19th April, 1969.

15.1 On the morning of 16th April, 1969, a western disturbance was apparently over Jammu and Kashmir, Punjab and adjoining Haryana with an associated trough extending southwestwards to Rajasthan and Sind (Fig. 15.1).

15.2 The upper winds over East Uttar Pradesh (upto 900 m) which were westerlies on 15th, changed to moderate to strong easterlies/southeasterlies indicating the formation of an upper air cyclonic circulation over the central parts of Uttar Pradesh. A trough line was also extending from this circulation southeastwards to Orissa and Gangetic West Bengal (Fig. 15.2).

15.3 The seasonal low on sea level chart lay over northeast Madhya Pradesh and adjoining parts of East Uttar Pradesh and Bihar. The 24 hour pressure changes over East Madhya Pradesh were -2 to -3 mb with the pressure anomalies of the order of -4 mbs. The 24 hour pressure changes over East Uttar Pradesh were, however, 1 to 2 mbs positive. This pressure change pattern was indicative of the intensification of the seasonal low over East Madhya Pradesh.

15.4 Under the influence of the above low pressure systems/cyclonic circulations, considerable incursion of moisture was occurring over most of north India and Madhya Pradesh. Surface dew points rose by 10-15°C over East Uttar Pradesh, Bihar Plateau and the adjoining areas (see inset chart in Fig. 15.1).
With the advance of the day, the circulation over Uttar Pradesh weakened into a trough, while a cyclonic circulation extending to 900 m developed over Gangetic West Bengal in the region where there was only a trough in the morning.

15.5 In the mid- and upper troposphere, a trough in westerlies was extending from West China southwestwards to Assam and adjacent states and Bangla Desh and a cut off low formed over Assam and adjacent states and Bangla Desh on 16th. Another trough in the upper westerlies was approaching northwest India. In between the two troughs, a ridge (with winds having well-marked anticyclonic curvature) extended from East Tibet to East Madhya Pradesh. West Bengal, Bihar State, Orissa, East Madhya Pradesh and East Uttar Pradesh were to the east of the ridge line.

15.6 Although there was a trough/low level cyclonic circulation over Gangetic West Bengal and neighbourhood and appreciable incursion of moisture was taking place, thunderstorm activity was practically nil over Bihar State, Gangetic West Bengal and Orissa, since these areas were to the east of the upper ridge line (making the upper air conditions unfavourable) Hence, large scale convective activity did not occur in spite of the other conditions being favourable.

15.7 On the next day i.e. 17th April 1969, the western disturbance over Jammu and Kashmir and neighbourhood was moving away eastwards across the Western Himalayas. The seasonal low over northeast Madhya Pradesh and adjoining Uttar Pradesh became marked even on the morning charts (03Z) with three closed isobars at 2 mb interval. The associated pressure anomalies were of the order of -4 to -6 mb in a general field of -2 to -3 mb over the country (Fig. 15.3). Consistant with the deepening of the seasonal low over northeast Madhya Pradesh, the lower tropospheric winds along Orissa and Gangetic West Bengal coasts were moderate to strong south/southwesterlies; they were about 20/30 kt in the morning increasing to 40/50 kt at some places in the evening.

15.8 The upper air circulation over Uttar Pradesh persisted in the lower troposphere and also became more marked on 17th morning with a trough extending southeastwards to northwest Orissa. A wind discontinuity was also extending eastwards from East Uttar Pradesh to Assam (See fig 15.4) In this wind discontinuity, a well-marked cyclonic circulation developed over eastern parts of Bihar and adjoining West Bengal during the course of the day and extended upto 1.5 kms a.s.l. (see (Fig. 15.4).

15.9 Surface dew point temperatures showed a further increase over Bihar Plateau, East Madhya Pradesh and Orissa on 17th morning (see inset chart in Fig. 15.3). The strong lower tropospheric southerlies were probably advecting considerable moisture into Gangetic West Bengal and Bihar State, as seen from the changes in the mixing ratio over Calcutta.

15.10 The sequence of tephigrams of Calcutta from 15th of April onwards showed the following features:

i) On the 15th there was no moist layer near the ground. By the next morning, a shallow moist layer developed with the typical inversion above it. The moist layer and the inversion were present on the 17th also. The tops of the moist layer on these days were :–

16	00Z	940 mb
	12Z	860 mb
17	00Z	910 mb
	12Z	870 mb

ii) There was incursion of moisture in the layer 700–500 mb also on the 17th (00Z). The 12Z tephigram of 17th showed considerable increase in moisture in the lower troposphere since the morning (Fig. 15.5). A nor'wester passed over Calcutta within an hour of this ascent.

15.11 The incursion of moisture was also seen on 17th morning surface chart in the form of a narrow tongue of high dew points extending from the coasts of Orissa and Gangetic West Bengal to Uttar Pradesh. There was a steep gradient in dew point temperatures over Bihar Plateau and adjoining areas (see Fig. 5.3).

15.12 The low over Assam and adjoining states and Bangla Desh in the mid- and upper troposphere moved away northeastwards and the trough in westerlies which was approaching northwest India on 16th moved to Punjab, East Rajasthan and northwest Madhya Pradesh by 17th 00Z. During the course of day, it rapidly moved further east and came over Bihar State, East Uttar Pradesh and East Madhya Pradesh by 12Z (Fig. 15.6).

15.13 The temperature distribution at 500 and 300 mb levels indicated cold air advection was also taking place over northeast India at these levels.

15.14 The low level convergence together with the appreciable incursion of moisture in the lower troposphere accompanied by the high level divergence associated with a trough in the westerlies lying to the west of the area caused an outbreak of nor'wester activity over Bihar State and the adjoining parts of West Bengal by the afternoon/evening of 17th (refer to last chart in Fig.15.6). The destabilisation due to the advection of cold air in the higher levels also took place.

15.15 The thunderstorm activity spread southeastwards to the eastern parts of West Bengal and also apparently into Bangla Desh during the course of the night. Nor'wester activity was fairly widespread in Bihar State and Gangetic West Bengal and isolated in Orissa. Calcutta reported a squall of 104 km per hour at 1744 hrs IST of 17th.

15.16 On the 18th April, the large positive pressure changes over East Madhya Pradesh and adjoining areas indicated that the seasonal low over northeast Madhya Pradesh was weakening (Fig. 15.7). In the lower troposphere a circulation was noticed over East Madhya Pradesh upto 0.9 km and winds along Orissa and West Bengal coasts continued moderate to strong southerlies/southwesterlies. This circulation was seen over Bihar Plateau by the evening.

15.17 The westerly trough was over West Bengal at 400 mb and above at 00Z (Fig. 15.8) and moved away further eastwards by 12Z. The westerlies to the rear of the trough were strong and a jet maximum was coming into Gangetic West Bengal. These conditions caused some thunderstorm activity over West Bengal, Bihar Plateau and neighbourhood. But it was very much less than on the previous day.

15.18 On 19th morning, the seasonal low over northeast Madhya Pradesh became less marked and the circulation in the lower troposphere over East Madhya Pradesh also weakened into a trough. Due to absence of conditions favourable for the occurrence of nor'wester activity both in the lower as well as in upper levels (viz. weakening of the surface low and the lower tropospheric cyclonic circulation and the moving away eastwards of the westerly trough in the upper troposphere) no thunderstorm occurred over West Bengal, Bihar State and Orissa on 19th.

15.19 This sequence of charts illustrates many of the favourable conditions for thunderstorm activity in Gangetic West Bengal, Bihar State and Orissa. The main points brought out are:-

i) Marked nor'wester activity occurred over Bihar State, Gangetic West Bengal and Orissa on 17th. The nor'wester activity commenced in the afternoon/ evening and the thunderstorms moved from northwest to southeast.

ii) The sudden increase in nor'wester activity on 17th was caused by the favourable low level and upper level conditions. In the low level the seasonal low over East Madhya Pradesh intensified, apparently under the influence of a passing western disturbance further north. The cyclonic circulation over Uttar Pradesh induced by the western disturbance and the intensification of the seasonal low over East Madhya Pradesh brought in a good incursion of moisture from the Bay into Bihar State, Gangetic West Bengal and Orissa and it was seen in the considerable rise of dew point temperatures over the area as well as the increase in the low level moisture content shown in Calcutta radiosonde ascents. The ascents took the characteristic features of nor'wester days. On 17th, a well-marked tongue of moist air extending from Orissa-West Bengal coasts to East Uttar Pradesh could be identified in the morning charts and there was a large gradient in dew point temperatures over Bihar Plateau and the adjoining areas where the thunderstorm outbreak took place.

iii) The favourable superposition of the moving upper westerly trough over the area of lower tropospheric convergence and influx of moisture, triggered off the thunderstorms on 17th. The passage of the upper trough over Calcutta is clearly illustrated by the time-section for Calcutta (Fig. 15.9).

iv) Apparently because of the lack of favourable upper air conditions, thunderstorm activity over Bihar State, Orissa and Gangetic West Bengal was very subdued on 16th, although the low level conditions were favourable.

v) Similarly the activity decreased by 18th and it became altogether nil on 19th as the upper trough moved away and the low level cyclonic systems also weakened.

15.20 Another significant point noticed in this sequence is that in the afternoon charts a cyclonic circulation was noticed over Bihar Plateau and neighbourhood on all the days while in the morning charts the prominent cyclonic circulation was further west. In the afternoon while the circulation developed over Bihar Plateau and adjoining Gangetic West Bengal, the main circulation further west noticed in the morning chart, became less marked. Thus there was a large diurnal shift of position of the low level circulations.

16. Widespread Thunderstorm Activity in Bihar State, Orissa and West Bengal - 18 to 25 April,1971

16.1 During the second half of April 1971 there was a spell of abnormal thunderstorm activity when fairly extensive thunderstorms occurred for about a week over large portions of north and central India. This spell was caused by the movement of a deep westerly trough across the country in the mid- and upper troposphere, and western disturbances and their induced lows in the lower tropospheric levels. A jet stream was also present in the upper troposphere. The occurrence of thunderstorms ahead of the upper westerly trough as it progressed eastwards across the country was clearly seen on all these days. As the basic synoptic conditions were nearly similar on all the days, the charts for two selected days (18th and 21st) alone are discussed in some detail in this section with special reference to Gangetic West Bengal,Orissa and Bihar State.

16.2 18th April:

16.2.1 On the morning of 18th, three well-marked cyclonic circulations were present over the country in the lower troposphere; they were over -

i) West Rajasthan and adjoining Pakistan

ii) West Uttar Pradesh and adjoining areas and

iii) Vidarbha and adjoining Madhya Pradesh.

Associated with the circulations over Uttar Pradesh and Madhya Pradesh, an east-west oriented discontinuity lay at 900 m asl over northeast India roughly along 25°N, with moderate to strong southerlies over Orissa, Gangetic West Bengal and Bihar Plateau and easterlies over Bihar Plains and sub-Himalayan West Bengal (Fig. 16.2.1).

16.2.2 With a low pressure area over Vidarbha and neighbourhood and a high over north and central Bay of Bengal, the pressure gradient over Gangetic West Bengal, Bihar State, Orissa, East Madhya Pradesh and Coastal Andhra Pradesh was quite steep (Fig. 16.2.2), and it was more marked in the evening when the east-west gradient was about 1 mb per degree of Long. Such a steep gradient implied considerable amount of cyclonic shear.

16.2.3 The radiosonde ascent of Calcutta showed that the air was quite moist in the lower and mid-troposphere (Fig. 16.2.3).

16.2.4 In the mid- and upper troposphere, a deep trough in westerlies extended from Punjab-Haryana to southeast Madhya Pradesh and Orissa at 500 mb level, sloping westwards with height. The trough was noticed upto 150 mb.

16.2.5 On this day (18th), thunderstorms were occurring even during the morning hours over Bihar Plateau and Gangetic West Bengal at some places. During the sabsequent 24 hrs, well-distributed thunderstorm activity was reported from the country north of 17°N east of 77°E, extending over a wide area close to the upper tropospheric trough line and in the forward sector of the trough. Thunderstorms were widespread in West Bengal, Bihar State, Orissa and East Madhya Pradesh, with reports of squalls from some places in these areas (see inset chart in Fig. 16.2.2). Calcutta had two squalls from a southwesterly direction.

16.3 21 April:

16.3.1 The trough in westerlies moved eastwards and on the morning of 21st extended from Bihar Plains to Coastal Andhra Pradesh between 500 mb and 200 mb, sloping slightly westwards with height. There was also a well-marked jet maximum over northeast India embedded in the south/southwesterlies ahead of the trough (Fig. 16.3.1). In the lower troposphere, a cyclonic circulation lay over Bihar Plateau and northeast Madhya Pradesh and it was seen more clearly on 12Z charts than on the morning charts. Another cyclonic circulation which was over Vidarbha and Marathwada in the morning shifted eastwards to southeast Madhya Pradesh, Telangana and adjoining Coastal Andhra Pradesh in the afternoon (Fig. 16.3.2). The circulation over Bihar Plateau extended upto the mid-troposphere. Tephigrams (00 and 12Z) of Calcutta showed a fair degree of moisture through a deep layer (Fig. 16.3.3).

16.3.2 During the next 24 hours, well-distributed thunderstorm activity occurred over northeast India in general. Thunderstorms were fairly widespread in West Bengal and Bihar State and scattered in north Orissa and East Madhya Pradesh (see last chart in Fig. 16.3.2).

16.3.3 The main points brought out by this sequence are:

i) On both the days (18th and 21st April) the lower and upper tropospheric conditions were favourable for the outbreak of thunderstorms. The low level cyclonic circulations were well-marked and of appreciable depth; in the upper troposphere, the trough in westerlies was also quite pronounced. A jet maxima was also seen over northeast India (on 21st). Considerable amount of moisture was available upto large heights. These led to generally widespread thunderstorm activity over large areas. The activity persisted for over a week, day after day, in Bihar State, Orissa and

West Bengal; this is uncommon.

ii) The westerly trough developed large amplitude over the country and moved rather slowly eastwards across the country. The shear across the trough line was very pronounced on some days, when the winds were northerly 50/60 kt to the west of the trough line and southerly 50/60 kt to the east of it. (For example, refer to 300 mb upper wind chart of 21/4/71). The more southerly track of the westerly trough over India was apparently due to the presence of a blocking 'high' to the north of the country. (Fig 16.3.4)

iii) Many of the radiosonde ascents of Calcutta during this period showed fairly moist air through a deep layer of the atmosphere. The low level inversion or stable layer was also not present. The lapse rate was also nearer to saturated adiabat than dry adiabat. Thus the tephigrams on this occasion were much different from the typical nor'wester tephigram discussed in para 5.5.3.

iv) During this period, thunderstorm activity was not confined to the afternoon/evening hours, but it was reported during morning hours also on some days. Morning thunderstorms – though not common – occur in Gangetic West Bengal, Bihar State and Orissa with deep migratory synoptic systems.

v) As the thunderstorm activity was over a prolonged period, and was also spread over a large area, surface dew point changes were not always very helpful. In fact dew point changes were even negative on some days. The gradient in dew points (referred to in para 5.6.3) was not so well-marked on these days.

vi) The lower tropospheric flow pattern during the period was very different from the seasonal flow over the Gangetic Plains. The seasonal west/northwesterly sweep over the Gangetic Plains was replaced by easterly/southeasterly winds in response to the formation and movement of low level cyclonic circulations across the area.

17. Thunderstorm Activity over Sub-Himalayan West Bengal and Assam and adjacent States - 16 to 19 April, 1970

17.1 As stated in para 6.4.2.2, thunderstorm activity in sub-Himalayan West Bengal, Assam and adjacent states is usually associated with the movement of a trough in the upper westerlies. The westerly trough discussed in Sec.16 in connection with thunderstorms over Gangetic West Bengal, Bihar State and Orissa, affected sub-Himalayan West Bengal and Assam also. In this section we will, therefore, discuss a case where there was no trough passage, but only a jet stream which, in association with a low level cyclonic circulation, produced a spell of thunderstorms in sub-Himalayan West Bengal and Assam and adjacent states.

17.2 Between 16th and 19th April, 1970, there was a spell of thunderstorm activity in Sub-Himalayan West Bengal and Assam and adjacent states. Over the rest of northeast India, there was very little activity.

17.3 In the lower troposphere, a cyclonic circulation which was over northwest Madhya Pradesh and adjoining East Rajasthan on 14 April, moved eastwards to northeast Madhya Pradesh and adjoining East Uttar Pradesh on 15th. It moved further eastwards across Bihar Plateau and Gangetic West Bengal and reached Bangla Desh and adjoining Assam and Meghalaya by 16th evening. The circulation was seen upto 1.5 km and on some charts as a feeble trough even upto 3.0 or 3.6 km. It persisted there on the 17th and subsequently weakened into a trough (Fig. 17.1).

17.4 On the surface chart, the movement of the above cyclonic circulation was reflected by a east/southeastward extension of the seasonal low to northeast India. There was also a certain amount of sequence of falling pressures and negative pressure departures. 0300Z Surface chart for one day, viz. 16.4.70, may be seen in Fig. 17.2.

17.5 The tephigrams of Gauhati showed increasing moisture over the area from 14th onwards. The incursion was initially more marked in near mid-tropospheric levels. During the period 14 to 17th, the air was moist to a high degree upto 500 mb. The tephigram of Gauhati for 15th 00Z is given as a sample (Fig. 17.3). It is noteworthy that the lapse rate was nearer to saturated than dry adiabat through deep layers.

17.6 In the upper troposphere, northeast India was under the influence of a ridge during this period. The ridge line (at 200 mb) travelled from Long. 80° to 92°E between 15th and 18th. A jet stream was present over northeast India during this period. Its axis was curving anticyclonically around the ridge pattern and was near about 25°N over northeast India at 200 mb level (Fig. 17.4). There was general strengthening of the upper westerlies over northeast India during this period and the core speed of the westerlies was well over 100 kts with pronounced vertical shear, as may be seen from the vertical time section of Gauhati (Fig. 17.5).

17.7 With the low level cyclonic circulation/trough, upper level jet stream and a deep layer of moisture, there was a spell of thunderstorm activity over sub-Himalayan West Bengal, Assam and adjacent states (see inset rainfall charts in Fig. 17.2). Apparently the jet maximum was powerful enough to offset the effect of the ridge.

18. Large Scale Convective Activity in Northwest India and Uttar Pradesh – (i) 11 to 15 May, 1969 and (ii) 9–10 April, 1972.

18.1 11 to 15 May, 1969.

18.1.1 During the period 11 to 15th May, 1969, there was a spell of large-scale thunderstorm activity over northwest India, Uttar Pradesh and Madhya Pradesh caused by the passage of western disturbances and their induced lows. In the mid- and upper troposphere, a well-marked westerly trough and a strong jet stream affected northern India. The low level systems were generally seen from surface upto 1.0 or 1.5 km while the westerly trough was noticed between 500 and 300 mb levels. The jet core had a speed of 100 kts. In this section we will discuss the charts for a selected day (12th), when the activity was most spread out.

18.1.2 On the morning of 12th a western disturbance was moving across Punjab, Haryana, Himachal Pradesh and adjoining areas, while an induced low lay over south Rajasthan and the adjoining northwest Madhya Pradesh (Fig. 18.1.1). The cyclonic circulation associated with the induced low extended upto 1.5 km. Another cyclonic circulation (extending upto 0.9 km) was also present over central parts of Madhya Pradesh (Fig. 18.1.2).

18.1.3 The induced low remained nearly stationary over South Rajasthan on the evening charts also while the other cyclonic circulation over Madhya Pradesh shifted slightly northwards and was seen over northwest Madhya Pradesh.

18.1.4 Under the influence of these cyclonic systems, easterly to southeasterlies prevailed over Uttar Pradesh and most of northwest India below 1.5 km, replacing the seasonal northwesterly flow.

18.1.5 Although pressure were falling generally over the whole country,the highest falls (about 4 mb) were over northwest India and adjoining Pakistan.

18.1.6 In the mid- and upper troposphere, a deep trough in westerlies was present over Afghanistan and Pakistan, with its axis roughly between 65°E and 70°E. Northwest India, West Uttar Pradesh and the adjoining areas were ahead of the trough line, under a vigorous southwesterly flow. In this southwesterly flow, a jet stream was present extending from southwest Rajasthan to West Uttar Pradesh hills and apparently a jet maxima was moving across the area. For instance, at Delhi the maximum strength of westerlies was about 40/50 kt on 10th and increased to 85 kt on 12th afternoon.

18.1.7 The tephigram of New Delhi showed an increase in moisture over the station on 10th, the near mid-tropospheric layer showing the maximum rise in the dew point values. On 12th morning, the layer from 700 mb to 550 mb was quite moist, though the layer below was relatively dry. The lower troposphere was highly unstable through a deep layer, with lapse rates close to dry adiabatic lapse rate. A comparison of the 12th (00Z) ascent (a thunderstorm day) with the 9th (00Z) ascent (a non-thunderstorm day) (Fig. 18.1.3) brings out the following feature:

i) There is no significant change in lapse rates

ii) In the lower troposphere air is slightly cooler (by about 3°C) on 12th

iii) On 12th there is considerable increase in moisture content at all the levels, the increase between 700 mb and 500 mb being more pronounced than below 700 mb.

18.1.8 Under the influence of the above discussed synoptic systems, fairly widespread thunderstorms were reported from northwest India, West Uttar Pradesh and the adjoining north Madhya Pradesh and East Uttar Pradesh on 13th morning (refer to last chart in Fig. 18.1.2). The precipitation amounts were higher over and near Western Himalayas. Over southwest Rajasthan where the air was dry (as shown by the tephigram of Jodhpur), there was no significant convective activity. The thunderstorms were mainly in the field of low level easterlies. The thunderstorms persisted even at 00Z of 13th, at some places. Delhi reported two squalls on the night of 12th.

18.2 9 to 10 April, 1972.

18.2.1 As an example of another instance of large scale thunderstorm activity over northwest India and Uttar Pradesh earlier in the season (in April), charts for 9-10 April, 1972 will be briefly discussed. In this case, also a western disturbance moved across the Western Himalayas while an induced low formed over West Rajasthan on 8th April. The induced low moved to southwest Uttar Pradesh and adjoining north Madhya Pradesh the next day (9th) when it become well-marked.

It was seen on the surface (Fig. 18.2.1) and in the lower tropospheric levels upto 1.5 km on this day (Fig. 18.2.2). In the lower tropospheric levels winds in the circulation were of speed 30/35 kt. Pressures were falling by 2 to 4 mb over the area and the pressure departure from normal was about -3 to -4 mb.

18.2.2 In the mid- and upper troposphere, a deep trough in westerlies extended from Afghanistan to Saurashtra, with its axis roughly along 70°E at 300 mb. Northwest India, Gujarat, Madhya Pradesh and Uttar Pradesh were ahead of the trough with very strong southwesterlies prevailing. An embedded jet stream running from Gujarat to West Uttar Pradesh across northwest Madhya Pradesh (with core speeds of 130 kts) was present in the southwesterly flow. The upper trough moved eastwards and was close to 75°E (at 300 mb) by the evening.

18.2.3 Under the favourable superposition of the lower and upper tropospheric conditions, large-scale convective activity occurred over north and central India on 9th (Fig. 18.2.3). Thunderstorm activity was mainly in the field of the low level easterlies and southerlies; the area also coincided with the forward position of the deep westerly trough.

18.2.4 On this occasion also, the tephigrams of Delhi showed a general increase of moisture, with pronounced increase in the near mid-tropospheric levels (about 700 mb) (Fig. 18.2.4).

19. Large-scale Convective Activity over the Central Parts of the Country Associated with Systems in the Westerlies - 8 to 10 April, 1972

19.1 We have briefly discussed the synoptic situation over the country from 8 to 10 April 1972 in the previous section (Sec. 18) in relation to the weather over northwest India and Uttar Pradesh. As large scale convective activity extended over the central parts of the country also on these days, we will again discuss the same situation in the present section, in some detail, with reference to Madhya Pradesh and Vidarbha.

19.2 On the morning of 8th April, 1972 an induced low pressure area lay over West Rajasthan (Fig. 19.1) with its associated cyclonic circulation extending upto 2.1 km asl (Fig. 19.2). A trough extended from the induced low southwards to east Vidarbha across the central parts of Madhya Pradesh and it was better noticed in the 06Z and 12Z charts. Pressures were falling by 0.5 to 1.0 mb over Rajasthan, Gujarat State and the central parts of the country where the pressure departures were also negative (-1 to -2 mb). In the mid- and upper troposphere, a trough in westerlies was over Pakistan and adjoining Rajasthan and Gujarat State. In response to the trough, the upper tropospheric winds over the central parts of the country and northwest India were strong southwesterlies; the axis of the jet stream was over south Rajasthan, northwest Madhya Pradesh and West Uttar Pradesh with core winds reaching about 120 kts.

19.3 During the next 24 hours, the induced low became well-marked and by the 9th morning moved to southwest Uttar Pradesh and adjoining north Madhya Pradesh (refer to Fig. 18.2.1). The pressure changes and departures over the area were about -2 to -4 mb. The associated cyclonic circulation in the lower troposphere was also well-marked with winds in its circulation reaching speeds of 30/35 kts. A trough line extended from the circulation southwards to Vidarbha (refer to Fig. 18.2.2).

19.4 The axis of the upper westerly trough at 300 mb was roughly along 70°E and it extended southwards upto East Central Arabian Sea across Saurashtra and Kutch. The upper tropospheric winds continued to be strong southwesterlies over the whole country north of Lat. 15°N and the jet axis was across north Madhya Pradesh with core winds of about 130 kts. During the preceeding 24 hours, scattered thunderstorms had occurred over Madhya Pradesh and Vidarbha, over the area corresponding to the axis of the low level trough. This region was also ahead of the westerly trough and generally to the south of the jet axis. The thunderstorms occurred after 12Z of 8th. As the induced low over north Madhya Pradesh and West Uttar Pradesh was quite intense on 9th morning, thunderstorm (or Cb) activity persisted at many stations in Madhya Pradesh in the morning of 9th also. In the subsequent 24 hrs, thunderstorm activity was generally widespread over East Madhya Pradesh and the adjoining parts of West Madhya Pradesh. Over the extreme western parts of Madhya Pradesh there was no thunderstorm activity.

19.5 By 10th morning, the induced low weakened and pressures rose heavily over north and central India where the departures also became large positive (Fig. 19.3). In the lower troposphere, only a feeble north-south oriented trough line persisted over central parts of Madhya Pradesh (Fig. 19.4), and by the evening it moved to the extreme eastern districts of East Madhya Pradesh and a general northwesterly sweep was setting in over northwest India and the central parts of country. The upper westerly trough moved rapidly from Long. 75°E in the morning to about Long. 82°E in the evening and was weakening. The jet stream was also weakening. Considerable fall in dew points was noticed over West Madhya Pradesh and Vidarbha, indicating the on-rush of drier air over the area. (See inset in Fig 19.3)

19.6 With the general weakening of the lower and upper tropospheric systems, thunderstorm activity considerably decreased over the country. There was practically no activity over Madhya Pradesh and Vidarbha.

19.7 The case history discussed in this section is illustrative of a spell of thunderstorm activity over Madhya Pradesh and Vidarbha associated with the movement of an induced low across the country. While the induced low moved across Rajasthan, West Uttar Pradesh and extreme north Madhya Pradesh, the associated trough extended southwards over Madhya Pradesh and Vidarbha. The extension of the trough southeast/southwards to Madhya Pradesh and Vidarbha is very characteristic. On such occasions, the seasonal wind discontinuity over southeast Madhya Pradesh and Vidarbha shffts westwards and merges with the trough extending southwards from the induced low. In the upper air, a deep westerly trough was affecting north and central India and the upper tropospheric flow over these areas was strong with an embedded jet stream in it. Thus the lower and upper tropospheric conditions were favourable for large-scale thunderstorm activity. As the lower level induced low and the upper westerly trough moved east, thunderstorm activity also moved eastwards and finally when the lower and upper systems moved away and weakened, weather also cleared in Madhya Pradesh and Vidarbha after 10th.

19.8 When the induced low over north Madhya Pradesh and Uttar Pradesh was well-marked, the thunderstorm activity occurred in the morning hours also particularly over north Madhya Pradesh.

19.9 Nagpur tephigram did not show any increase in moisture even at 1200Z of 8th; only by 9th 00Z considerable increase in moisture was noticed at all the levels.

19.10 In this case, we had a well-marked trough and a strong jet stream over north Madhya Pradesh. There was also a general strengthening of the westerlies over the northern and central parts of the country and north Peninsula. At Nagpur, the maximum winds reached 100 kts and at Gwalior, 130 kt. In many cases of thunderstorm activity over the central parts of the country, in winter and earlier part of the hot weather period, a jet maxima is a common feature. When the jet stream comes far to the south of its normal position, to Vidarbha, south Madhya Pradesh or north Peninsula, it is a favourable situation for development of induced lows and occurrence of large scale weather over Madhya Pradesh and Vidarbha. A typical situation in March, 1962 showing large scale thunderstorm activity, with a jet maximum but without a trough is illustrated in Fig. 19.5. On this occasion, there was a cyclonic circulation or trough in the lower levels. Severe squalls and hailstorms occurred in east Vidarbha, southeast Madhya Pradesh and adjoining West Madhya Pradesh.

20. Thunderstorm Activity over the Peninsula Associated with Well-marked Seasonal Wind Discontinuity over the Peninsula in the Lower Levels - 16 to 17 April,1971

20.1 On the morning of 14th April, 1971 an induced low pressure areas lay over northwest Madhya Pradesh and adjoining East Rajasthan, with the associated cyclonic circulation extending upto 1.5 km asl. A wind discontinuity was running from this circulation southeastwards to East Madhya Pradesh and then southwards to the extreme south Peninsula. There was no marked contrast in the moisture content on either side of the discontinuity in the north Peninsula and the air was generally dry there. In the middle and upper troposphere, a trough in the westerlies extended from West Tibet to Andhra Pradesh, with its axis at 300 mb, roughly along 80°E. During the previous 24 hrs, weather was mainly dry over the Peninsula except for very isolated thunderstorms along the discontinuity line.

20.2 By the next morning (15th) the induced low over northwest Madhya Pradesh and neighbourhood persisted more or less over the same area (Fig. 20.1), while two cyclonic circulations developed in the seasonal wind discontinuity - one over East Madhya Pradesh, east Vidarbha and adjoining areas, extending upto 0.9 km and the other over Telangana and neighbourhood extending upto 0.6 km (Fig. 20.2). The formation of these cyclonic circulations in the wind discontinuity suggested greater cyclonic vorticity over these areas. There was also a general increase in the moisture content in the lower troposphere over the north Peninsula. The trough in the westerlies in the mid- and upper troposphere moved slightly eastwards and became more marked. Its axis lay at 300 mb from central Tibet to Coastal Tamil Nadu across East Madhya Pradesh. There was an increase in thunderstorm activity over the Peninsula mostly along and near the discontinuity line and to the east of it. By the evening (of 15th), a well-marked cyclonic circulation developed over South Interior Karnataka in the seasonal wind discontinuity (Fig. 20.3). This could have been the same circulation that was noticed over Telangana in the morning.

There was also a flow of southeasterlies into south Peninsula from the Bay in the lower troposphere. Associated with these changes, there was well-distributed thunderstorm activity in Kerala, south Interior Karnataka and Interior Tamil Nadu during the 24 hours ending at 0830 hrs of 16th (refer to inset chart in Fig. 20.1). There was also isolated thunderstorm in Telangana. These thunderstorms were mainly to the rear of the westerly trough in the field of north westerly/northerly upper flow. The heavy thunderstorms in Orissa and the adjoining Coastal Andhra Pradesh were due to the low over East Madhya Pradesh and the forward portion of the deep westerly trough.

20.3 On 16th morning, the circulation over East Madhya Pradesh lay over east Vidarbha and adjoining southeast Madhya Pradesh extending upto 1.5 kms asl (Fig. 20.4). The cyclonic circulation over south Interior Karnataka apparently moved westwards into the Arabian Sea off south Maharashtra-Karnataka coasts and was noticed on surface and also in the lower troposphere in very low levels. The seasonal wind discontinuity extended from east Vidarbha southwestwards to off Maharashtra coast. Large differences in dew points were noticed between the two sides of the discontinuity line.

20.4 The trough in the middle and upper troposphere moved further eastwards and was extending from East Tibet to off Tamil Nadu coast at 300 mb. As a result, the wind flow over the Peninsula at these levels was from northwest/north and the speeds were of the order of 30-40 kt.

20.5 On the 17th morning, the circulation over Vidarbha and neighbourhood became less-marked. The seasonal wind discontinuity extended at 0.9 km asl from a fresh cyclonic circulation (induced low) over northwest Madhya Pradesh southwards to Kerala (Fig. 20.5). Marked contrast in dew points was continued to be noticed between the two sides of the wind discontinuity. The trough in the middle and upper troposphere now moved further eastwards into the Bay. The sweep of northwesterlies over the Peninsula in the upper troposphere was maintained on this day also. There was well-distributed thundershowers over the Peninsula to the south of the position of the wind and moisture discontinuity of 16th (see last chart of Fig. 20.5). The weather occurred over an area which was in the rear of the trough in the upper troposphere. During the next 24 hrs there was scattered thunderstorm activity over the Peninsula. Subsequently the thunderstorm activity decreased.

20.6 The following features are noteworthy in the sequence of weather discussed above:

i) Thundershower activity over the Peninsula in association with the seasonal wind discontinuity is very isolated (as on 14th) unless the discontinuity line becomes well-marked and some vortices form along the line, and an inflow of moisture into the Peninsula also takes place.

ii) The passage of an induced low across the central parts of the country and changes in the location and intensity of the anticyclone over the Bay may contribute to the seasonal wind discontinuity becoming well-marked and the flow of moisture into the Peninsula. These conditions were observed in the present case between 15 and 17 April.

iii) The seasonal wind discontinuity makes minor east-west oscillations across the Peninsula. The movement of the wind discontinuity and the cyclonic circulations embedded in it, is difficult to predict.

iv) Thunderstorm activity is generally over the area close to the seasonal discontinuity line and in the air stream to the east and south of the wind discontinuity which is usually moist.

v) In the present case, a deep trough in westerlies extending well south, moved eastwards and a moderate to strong northwesterly/northerly flow set in over the Peninsula. Such a flow in low latitudes is also favourable for upper divergence. In the present case, the well-marked seasonal wind discontinuity with embedded vortices in it together with the favourable upper air conditions caused a spell of well-distributed thunderstorm activity in the Peninsula on 16, 17 and 18th April.

21. Low Pressure Area/Trough moving Westwards Across the Peninsula to Extreme Southeast Arabian Sea – 13th to 16th April 1970.

21.1 This case history was described in Sec.10 of FMU Rep.No. III-2.1 with reference to the weather over the sea areas. Now we will briefly discuss the same synoptic situation in so far as it affected the weather over the Peninsula. In contrast to the case history discussed in the previous section (Sec. 20), we have in the present case a general easterly flow over the Peninsula in the lower troposphere and a disturbance in the easterlies moved west across the south Peninsula, causing weather.

21.2 A low pressure area which lay over the Andaman Sea on the morning of 9th April, 1970, moved westwards and reached Comorin – Sri Lanka and adjoining South Tamil Nadu coast on 13th morning (Fig. 21.1). The circulation associated with the low extended upto 1.5 kms asl (Fig. 21.2). As the centre of the low/cyclonic circulation was to the south of India, the system could be seen over Sri Lanka and south Peninsula only as a north–south oriented trough in general easterly flow. (In this connection vide the discussion in para 12.4 of FMU Rep. No. III–4.1). On this day another low was also present in the east Arabian Sea off Karnataka coast. A general easterly flow prevailed over the Peninsula in the lower troposphere and the seasonal wind discontinuity was absent. On this day the rainfall was mostly over Sri Lanka, with isolated thunderstorms over the extreme south of the Peninsula.

21.3 The low moved westwards across the Comorin and lay over Lakshadweep – Maldives area on the morning of 14th (Fig. 21.3 and 21.4). The cloud patch associated with the system also showed a progressive westward movement. As the low pressure area moved across Comorin and extreme south Peninsula, rainfall increased in Tamil Nadu and Kerala and was fairly widespread over the south Peninsula to the south of Lat. 12°N. At many places (particularly in the western parts of the south Peninsula) Cb clouds and thunder were reported.

21.4 By the next day (15th), the low moved further westwards and lay over the southeast Arabian Sea to the west of Lakshadweep-Maldives area. The rainfall decreased but still it was scattered over the south Peninsula south of Lat. 13°N (see inset chart in Fig. 21.3). Subsequently, as the low moved away further westwards and weakened, the weather over the Peninsula rapidly improved.

21.5 As the central region of low was well to the south of the country, located in the near equatorial region, the system was seen over the Indian sea area only as a north-south trough in easterlies moving westwards across Comorin and the south Peninsula. The passage of the trough could be seen in the vertical time-sections of Trivandrum and Minicoy (Fig. 21.5). The trough portion over India had an easterly slope with height. In the western parts of the south Peninsula where the terrain is hilly, thunderstorms were reported at a number of places.

21.6 Due to lack of observations from the near equatorial region, the analyst had to lean heavily on the satellite data to trace this disturbance.

21.7 When the disturbance was well away to the east, the weather over the Peninsula was practically dry (on 12th) except for isolated light thunderstorms in south Interior Karnataka and Kerala. However, when the low reached Comorin area on 13th, there was a considerable increase in rainfall and it was fairly widespread in Sri Lanka on 13th and in ~~and the adjoining~~ south Tamil Nadu and Kerala on 14th. Rainfall in the south Peninsula persisted on the next day also (15th) in the rear of the disturbance. Subsequently as this low moved away far to the west, weather considerably improved over south Peninsula.

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DIAGRAMS

FIG. 5-1 TYPICAL TEPHIGRAM OF CALCUTTA ON A DAY OF NOR' WESTER. 00 GMT. 21 APRIL 69

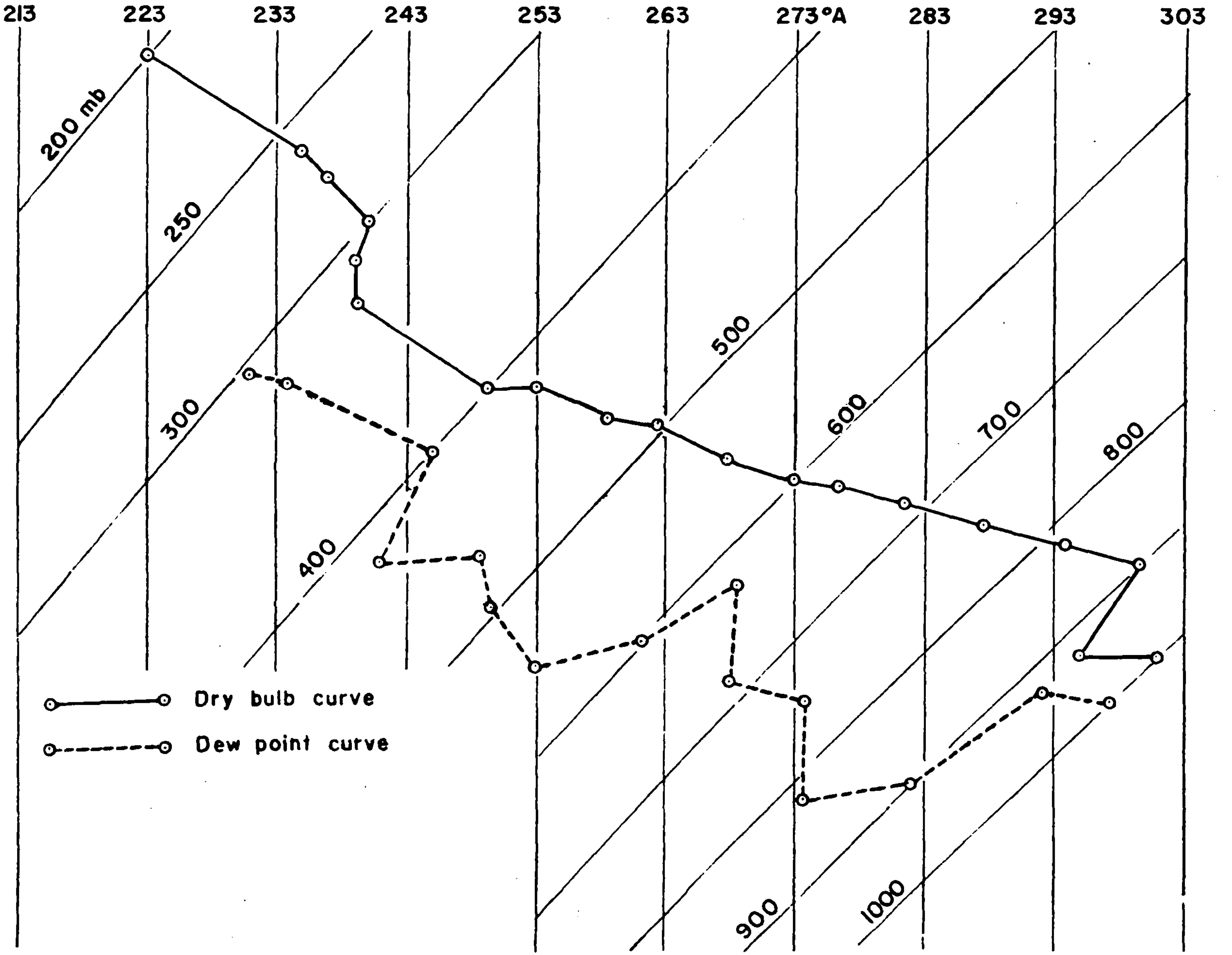


FIG. 5·2 PROXIMITY SOUNDING FOR CALCUTTA 12GMT 17 APR.69

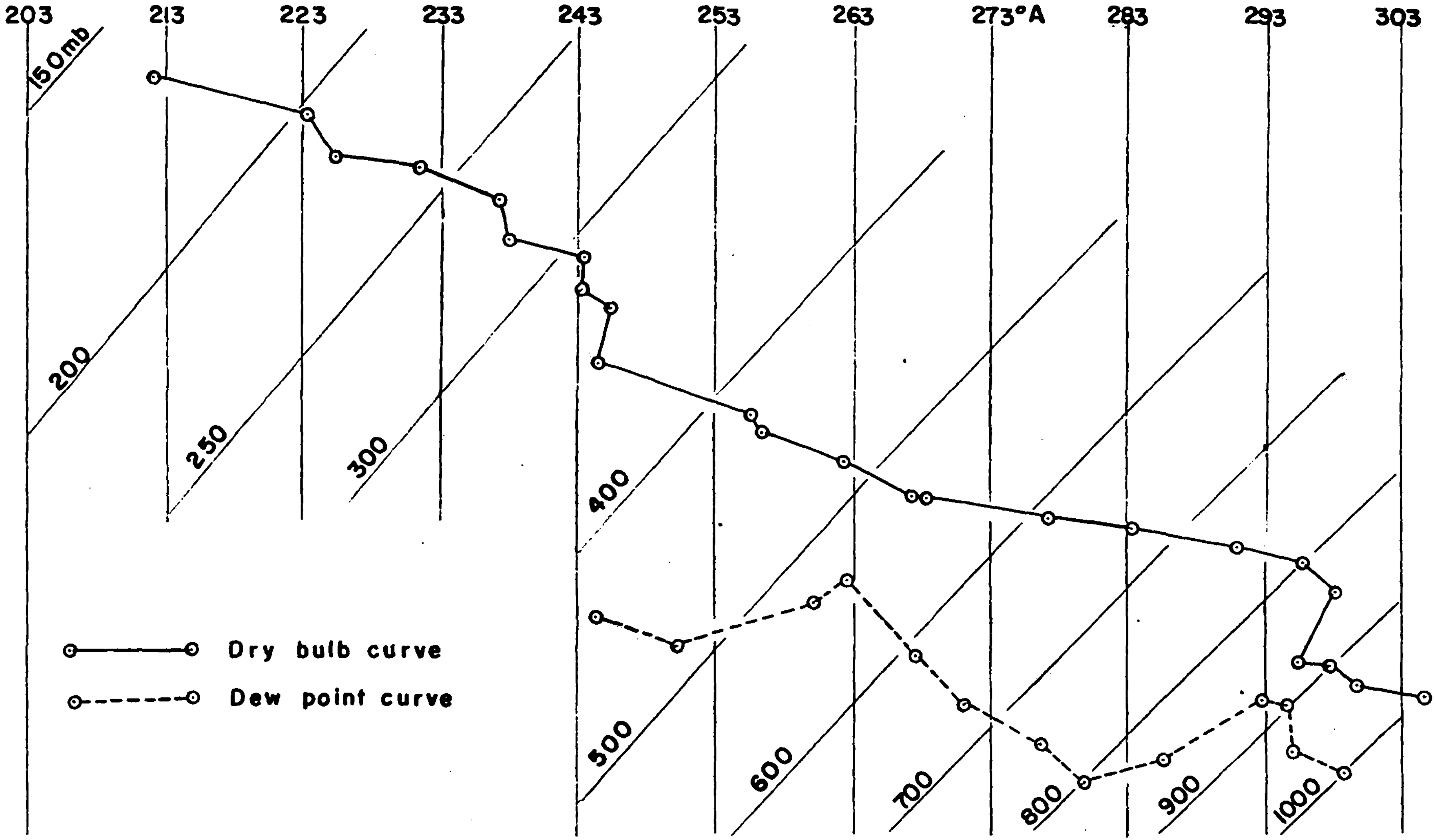


FIG. 5·3

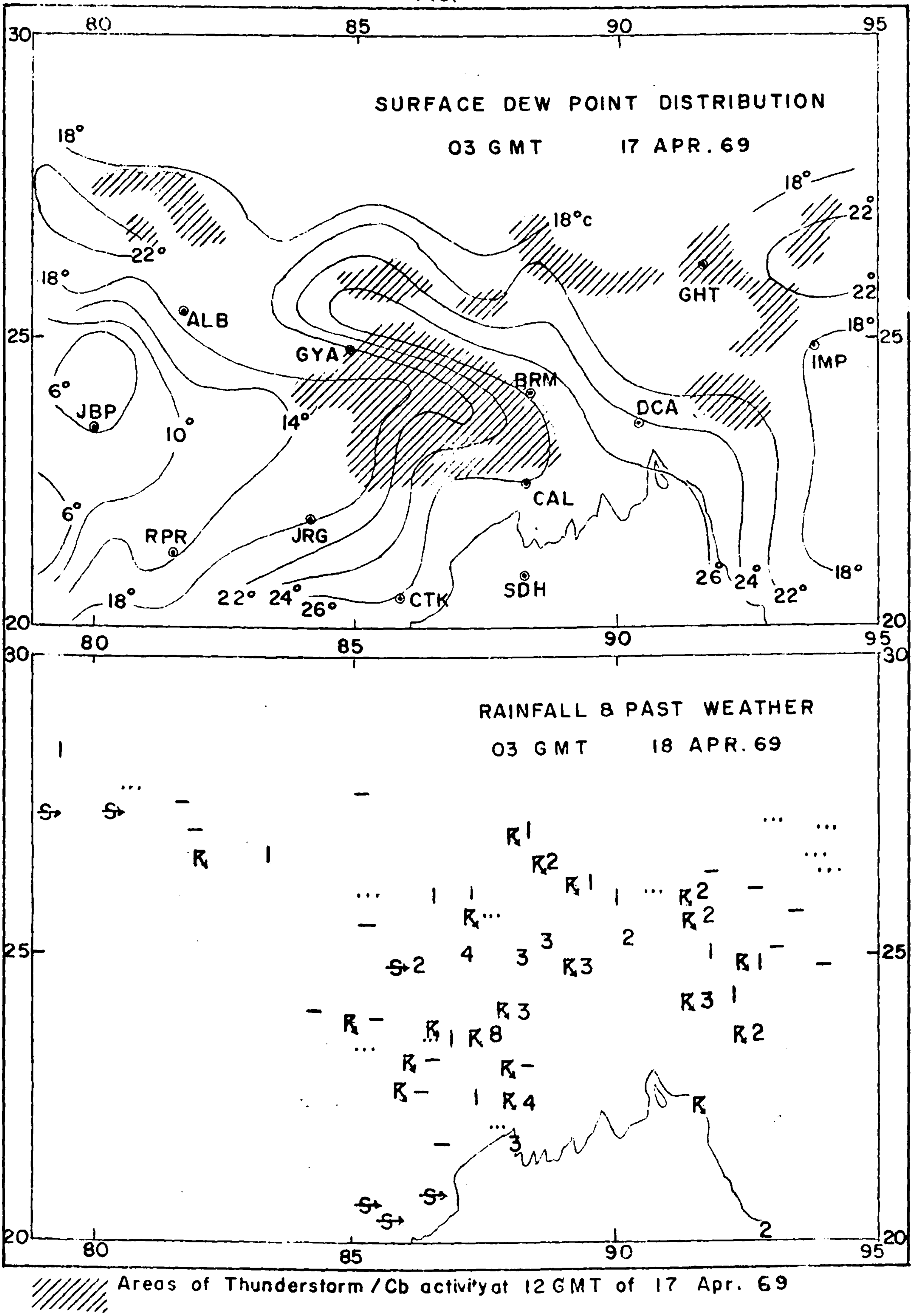

SURFACE DEW POINT DISTRIBUTION
03 GMT 17 APR. 69
ALB
GYA
JBP
RPR
JRG
CTK
SDH
CAL
BRM
DCA
GHT
IMP
RAINFALL & PAST WEATHER
03 GMT 18 APR. 69
Areas of Thunderstorm / Cb activity at 12 GMT of 17 Apr. 69

FIG. 6·1(a) MEAN TEPHIGRAM OF GAUHATI FOR THUNDERSTORM & NON-THUNDERSTORM DAYS IN APRIL (1968-72) 12 GMT

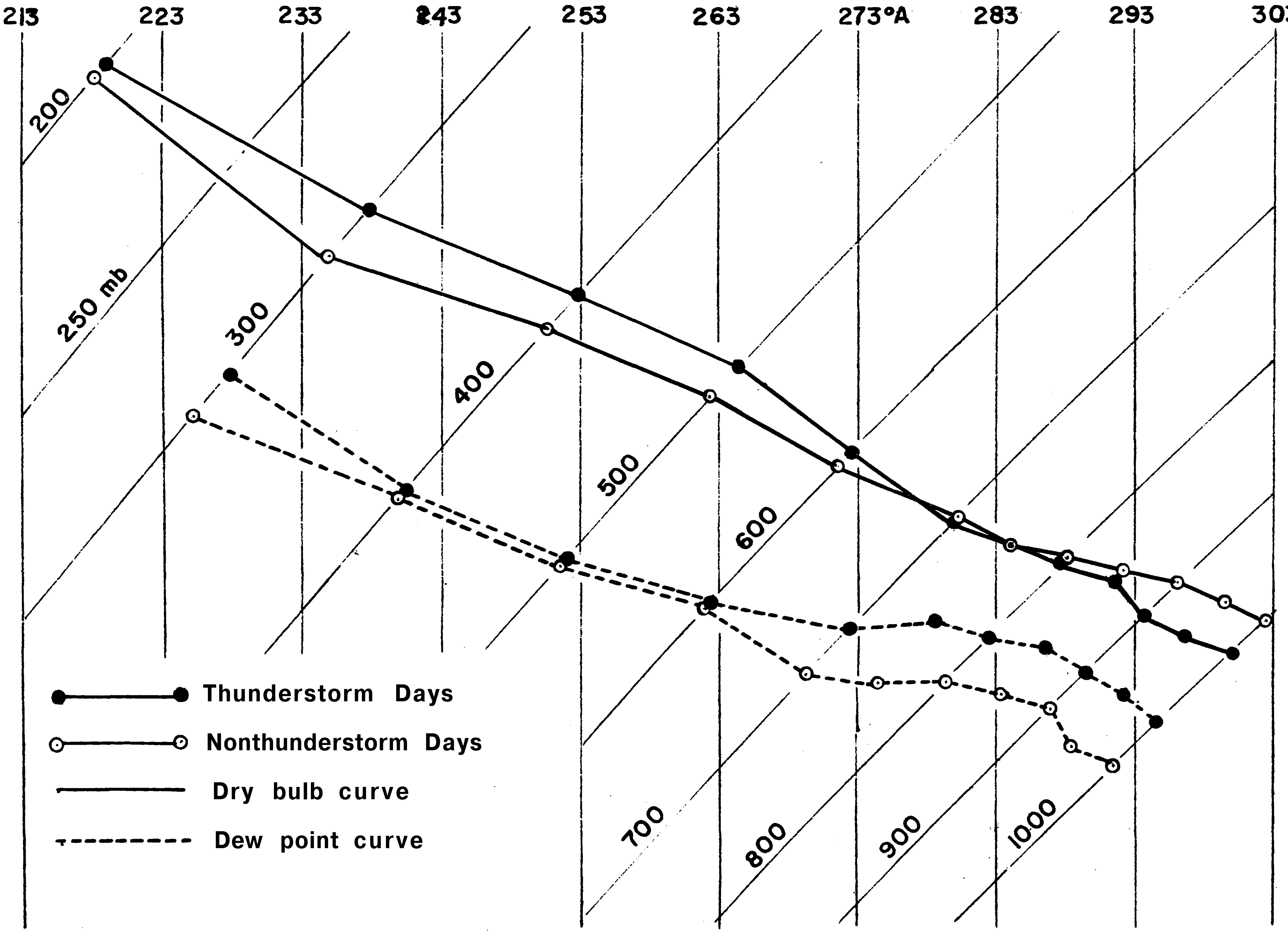


FIG. 6·1(b) MEAN TEPHIGRAM OF GAUHATI FOR THUNDERSTORM & NON-THUNDERSTORM DAYS IN MAY (1968-72) 12GMT

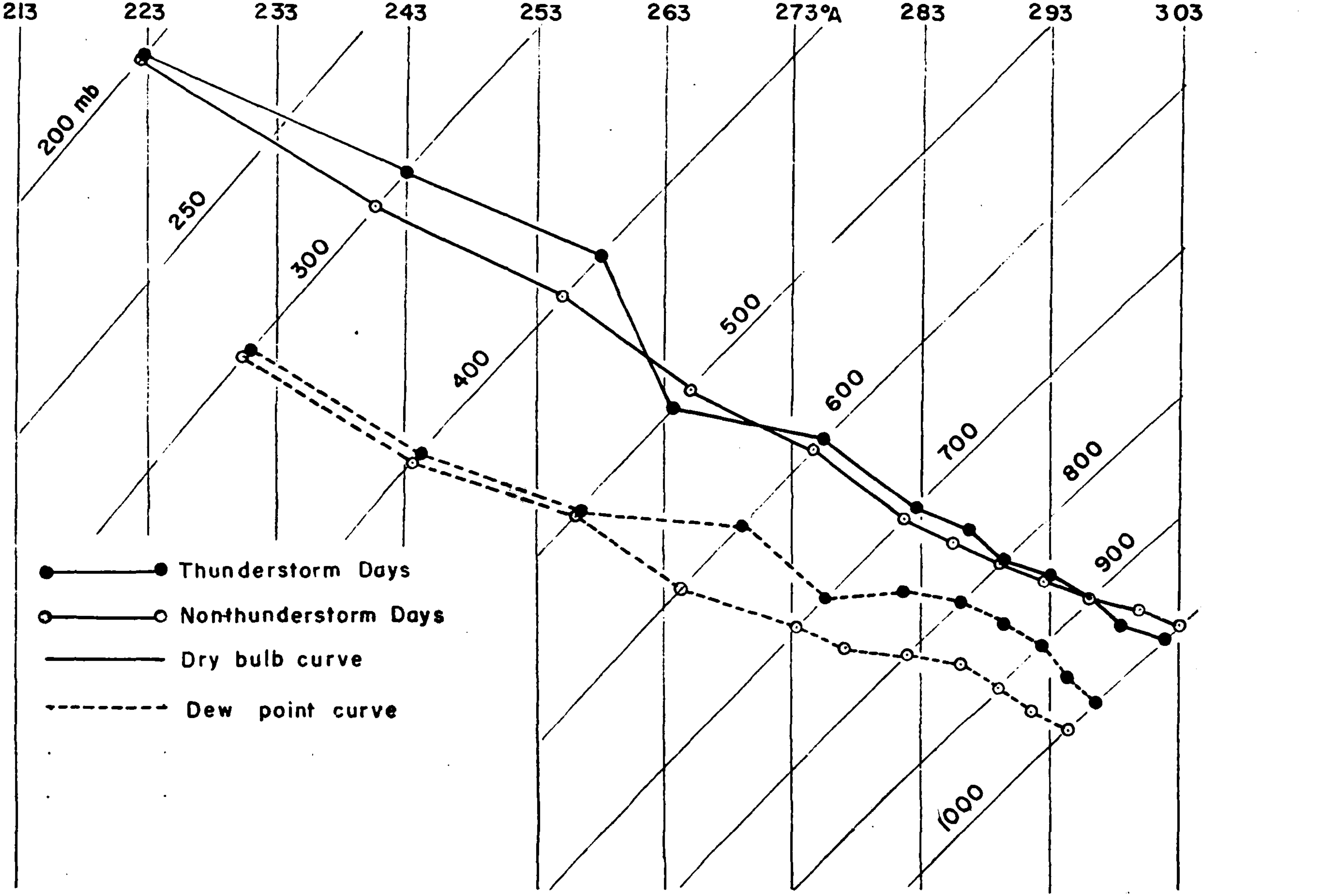
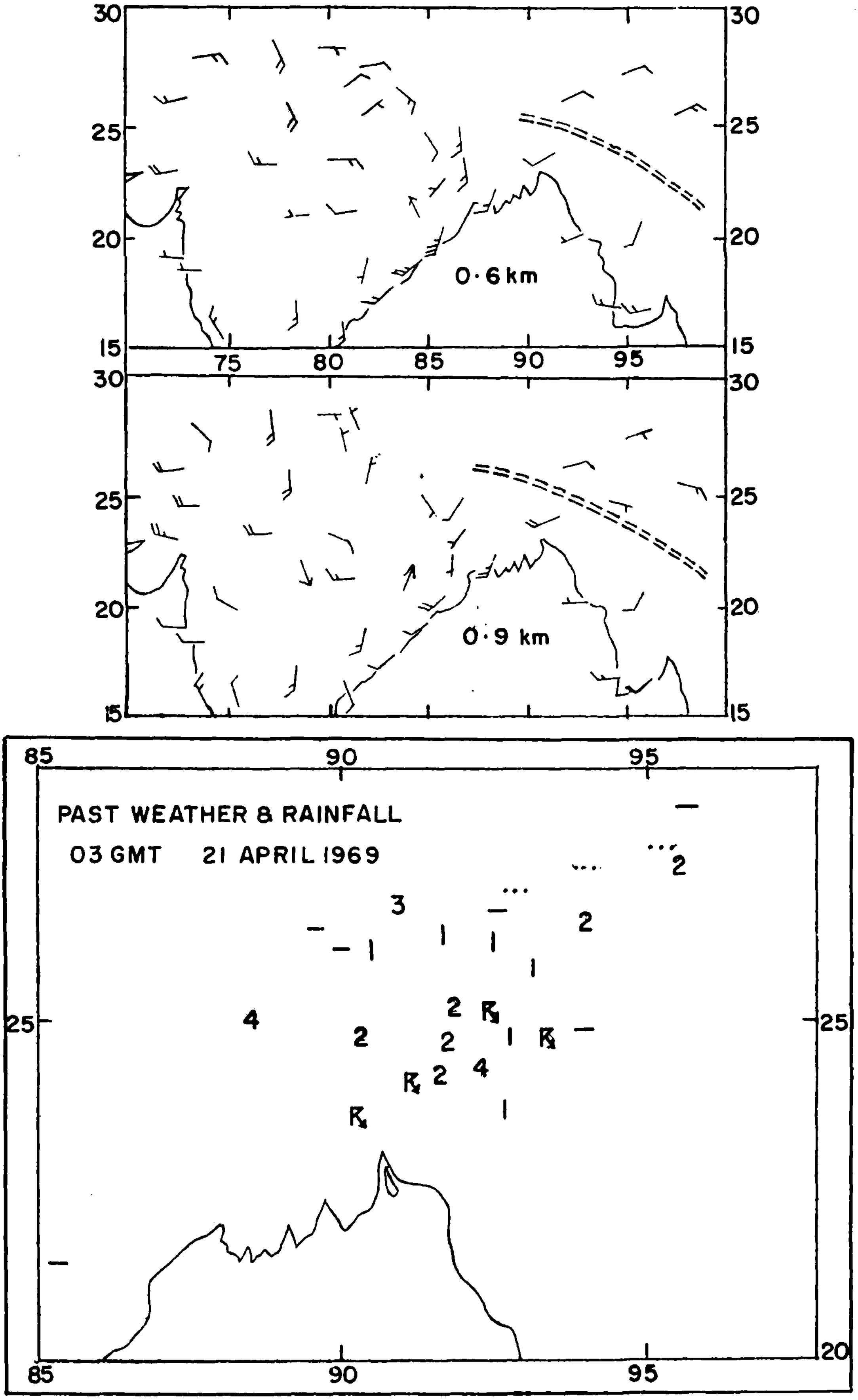
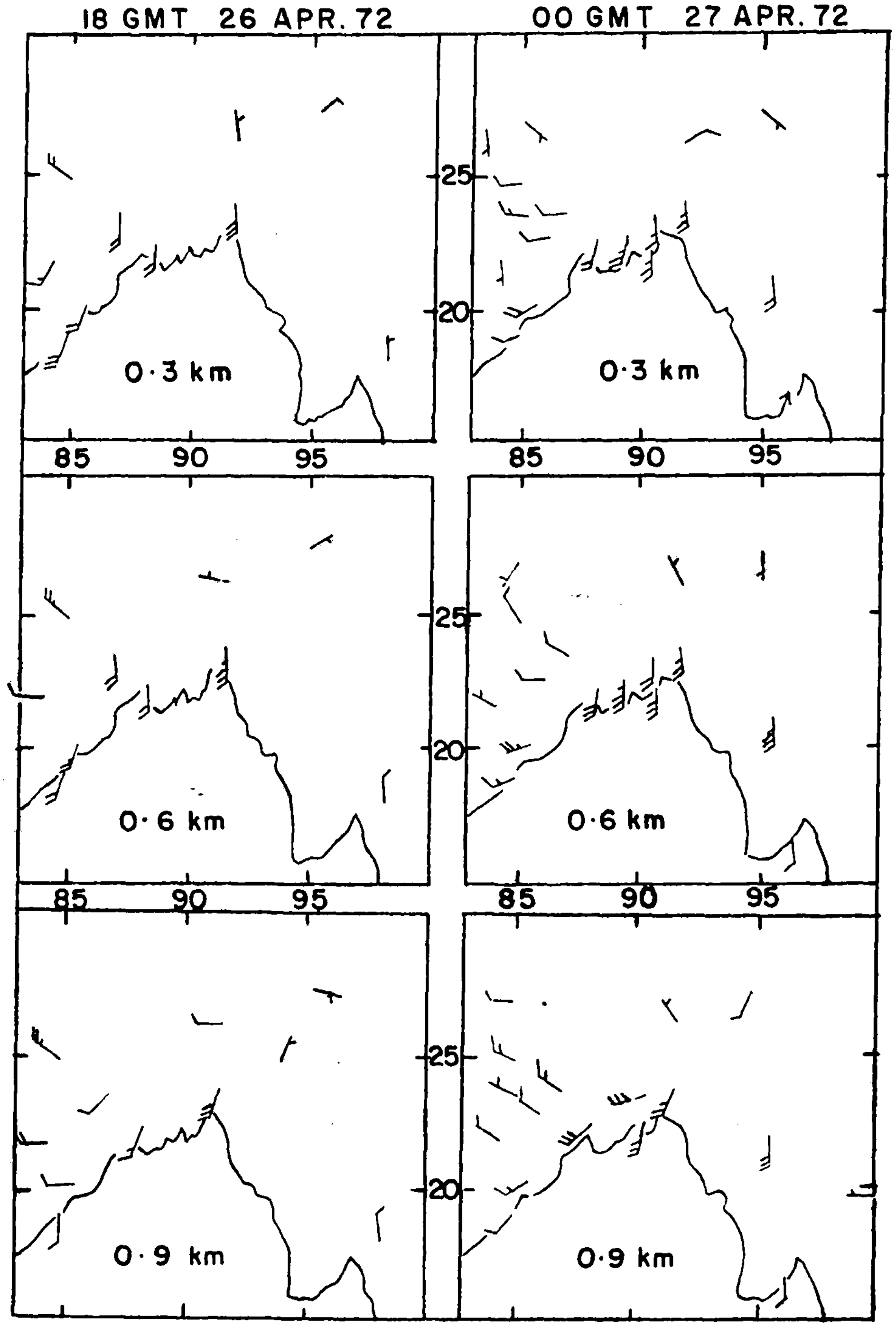


FIG. 6·2 UPPER WINDS 00 GMT 20 APRIL 1969.



======== Line of Discontinuity

FIG. 6·3 UPPER WINDS



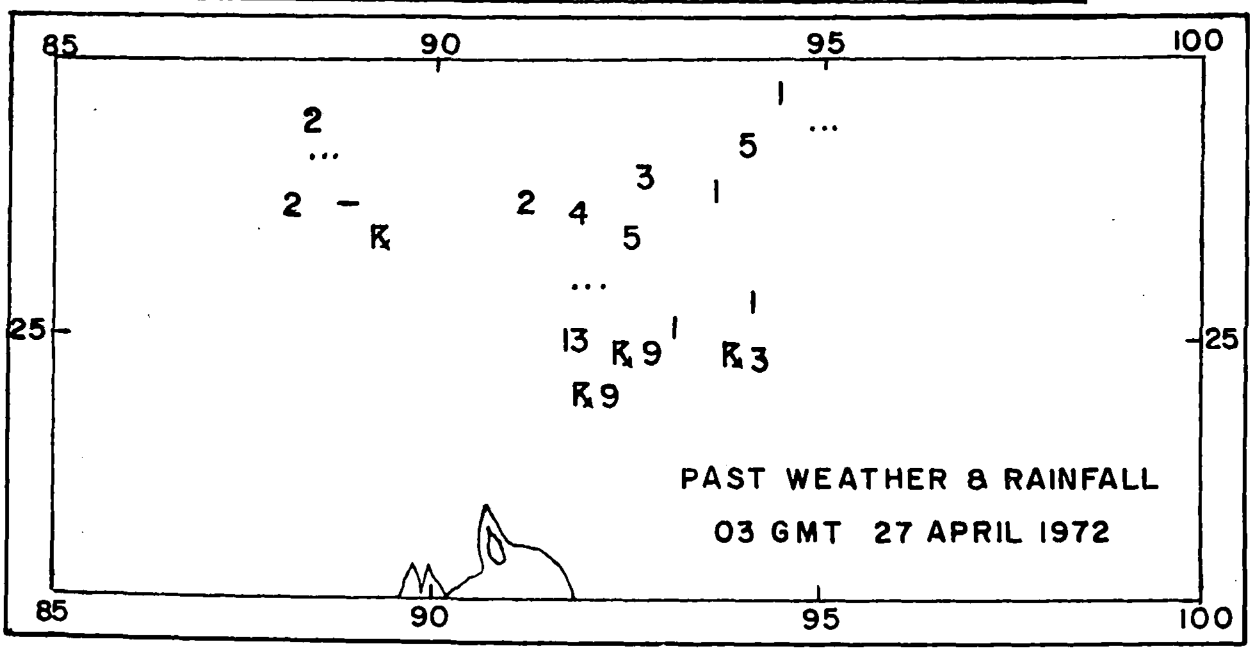
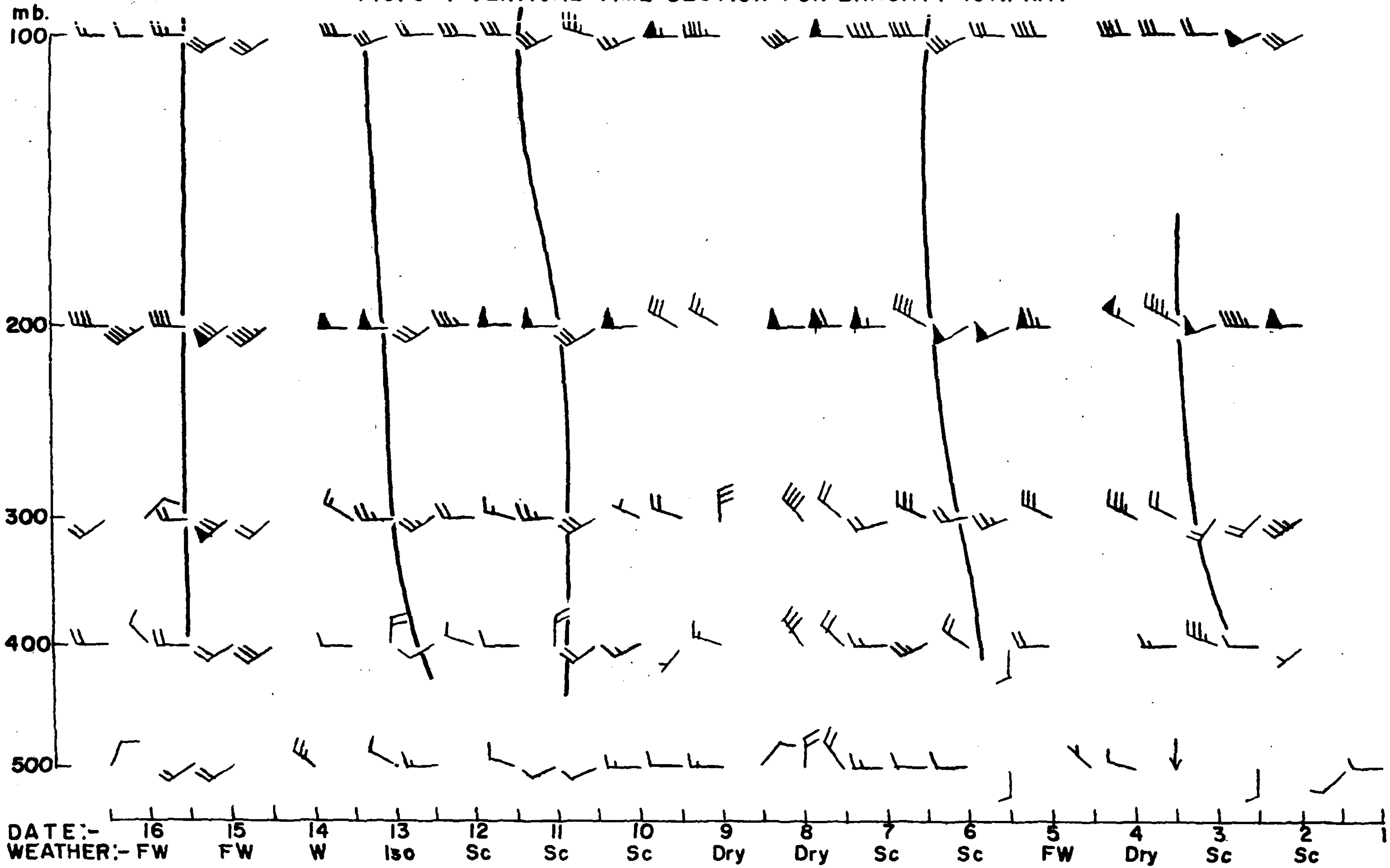


FIG. 6·4 VERTICAL TIME SECTION FOR LHASA: 1-16 APR. 71



Note: Spatial distribution of rainfall in the meteorological sub-divisions of sub-Himalayan West Bengal, Assam and Arunachal Pradesh is given below each date.

FIG. 7·1 MEAN TEPHIGRAMS FOR DELHI FOR DAYS OF SCATTERED/WIDESPREAD THUNDERSTORM/DUSTSTORM AND DAYS OF NON-THUNDERSTORM/DUSTSTORM WITHIN 250 km. OF THE STATION (1968-73) (APRIL-MAY)

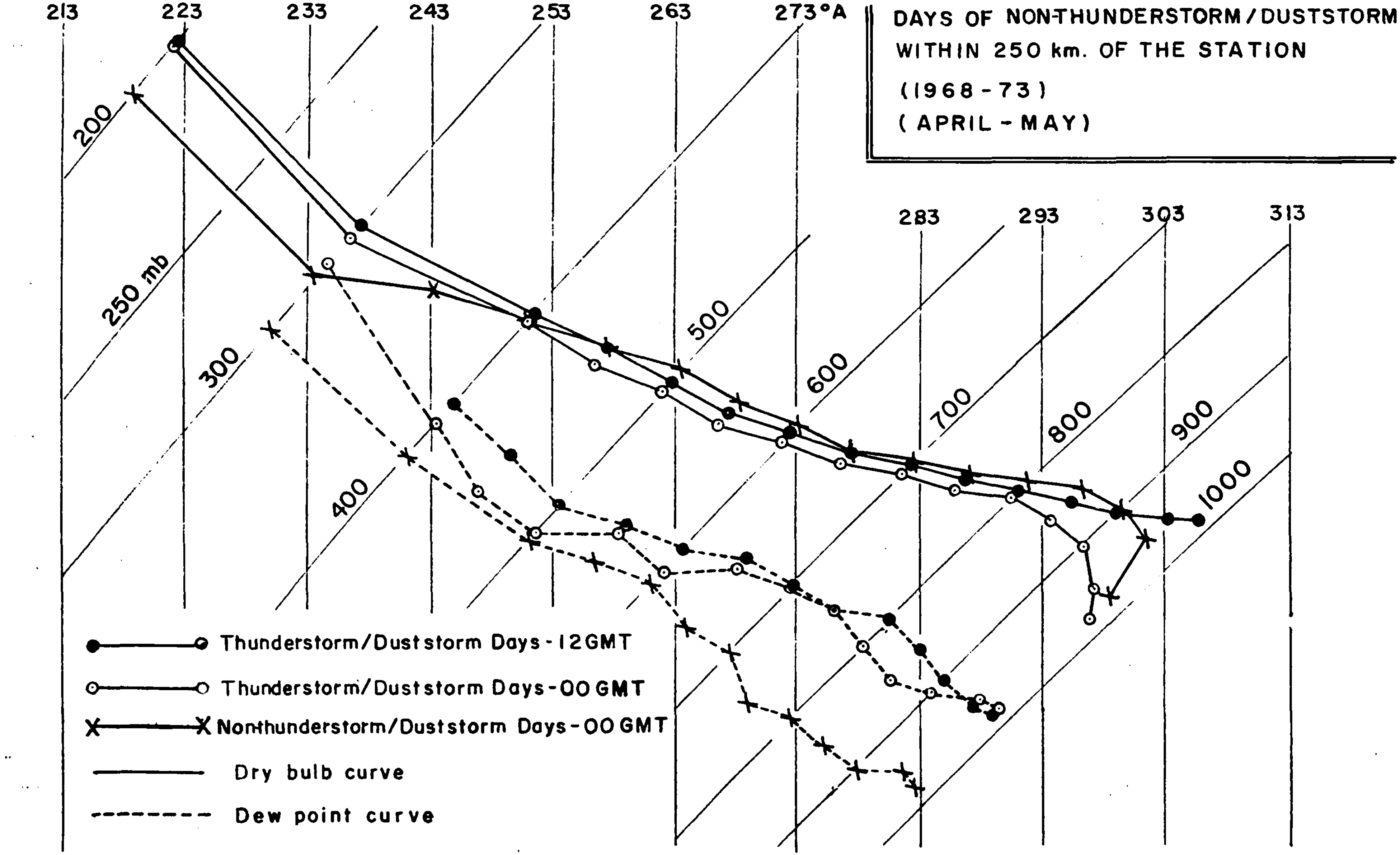
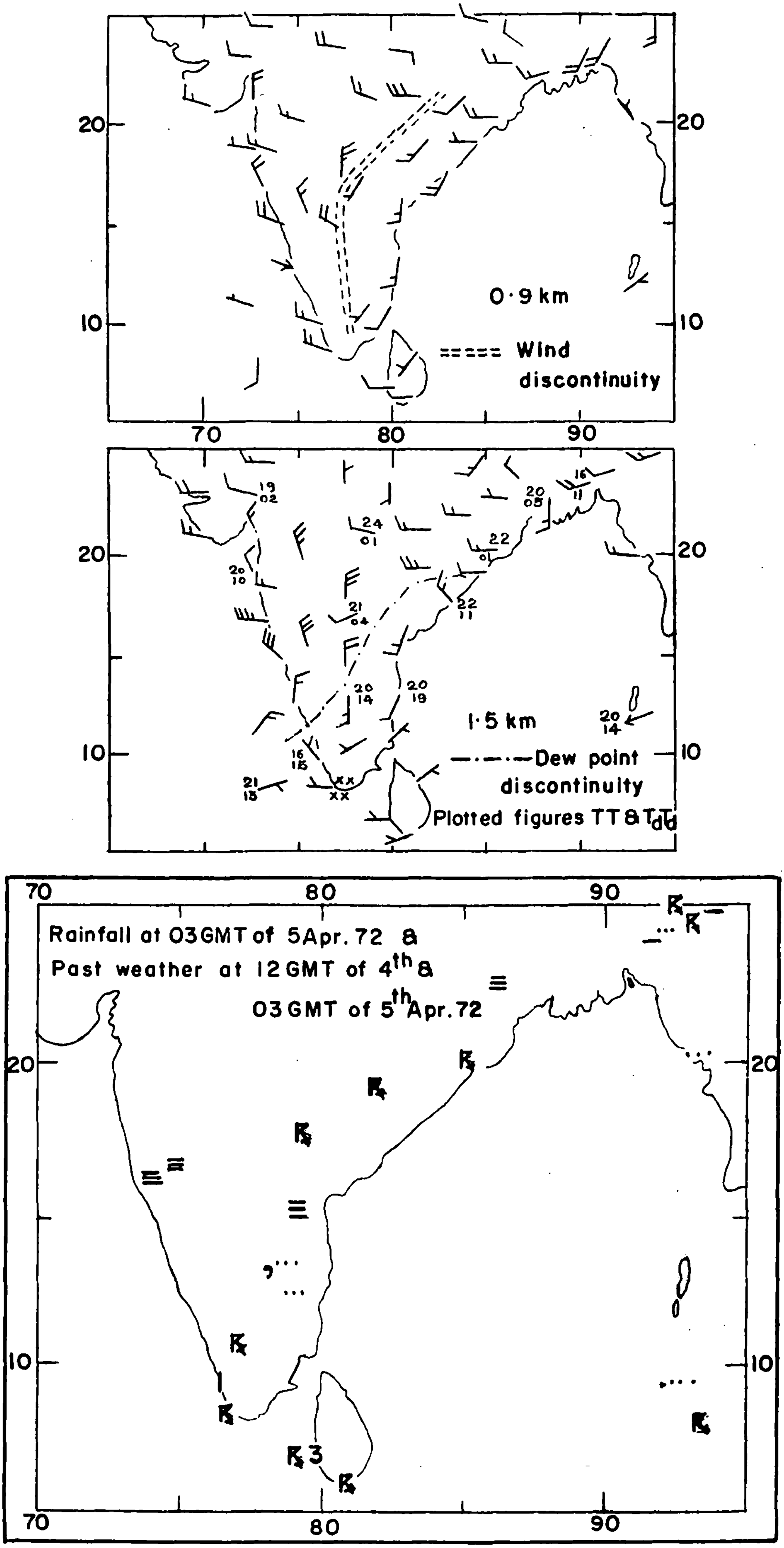


FIG. 8·1 UPPER WINDS 00 GMT 4 APRIL 1972



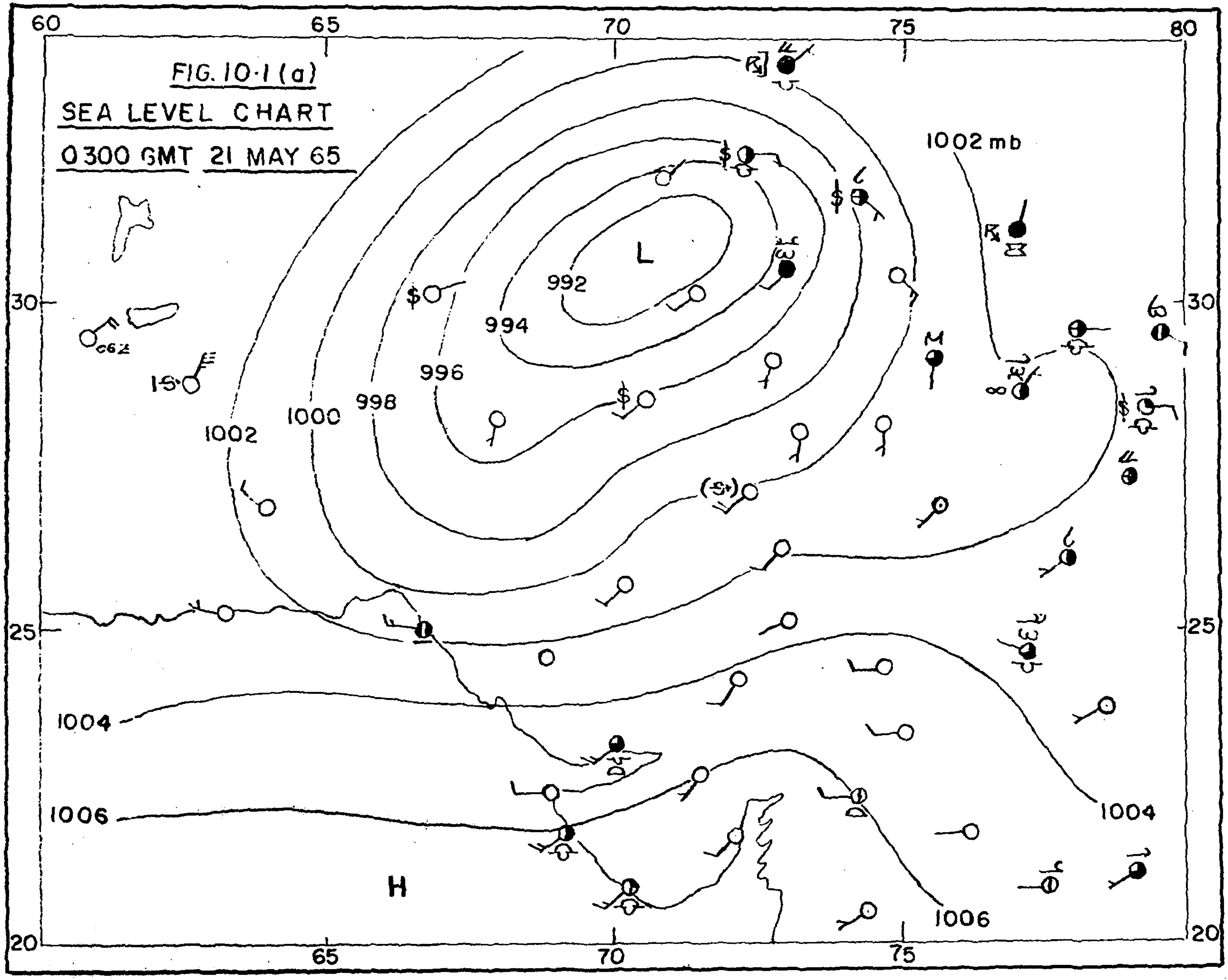


FIG. 10·1 (a)
SEA LEVEL CHART
0300 GMT 21 MAY 65
1002 mb
1002
1000
998
996
994
992
1004
1006
L
H
60
65
70
75
80
30
25
20

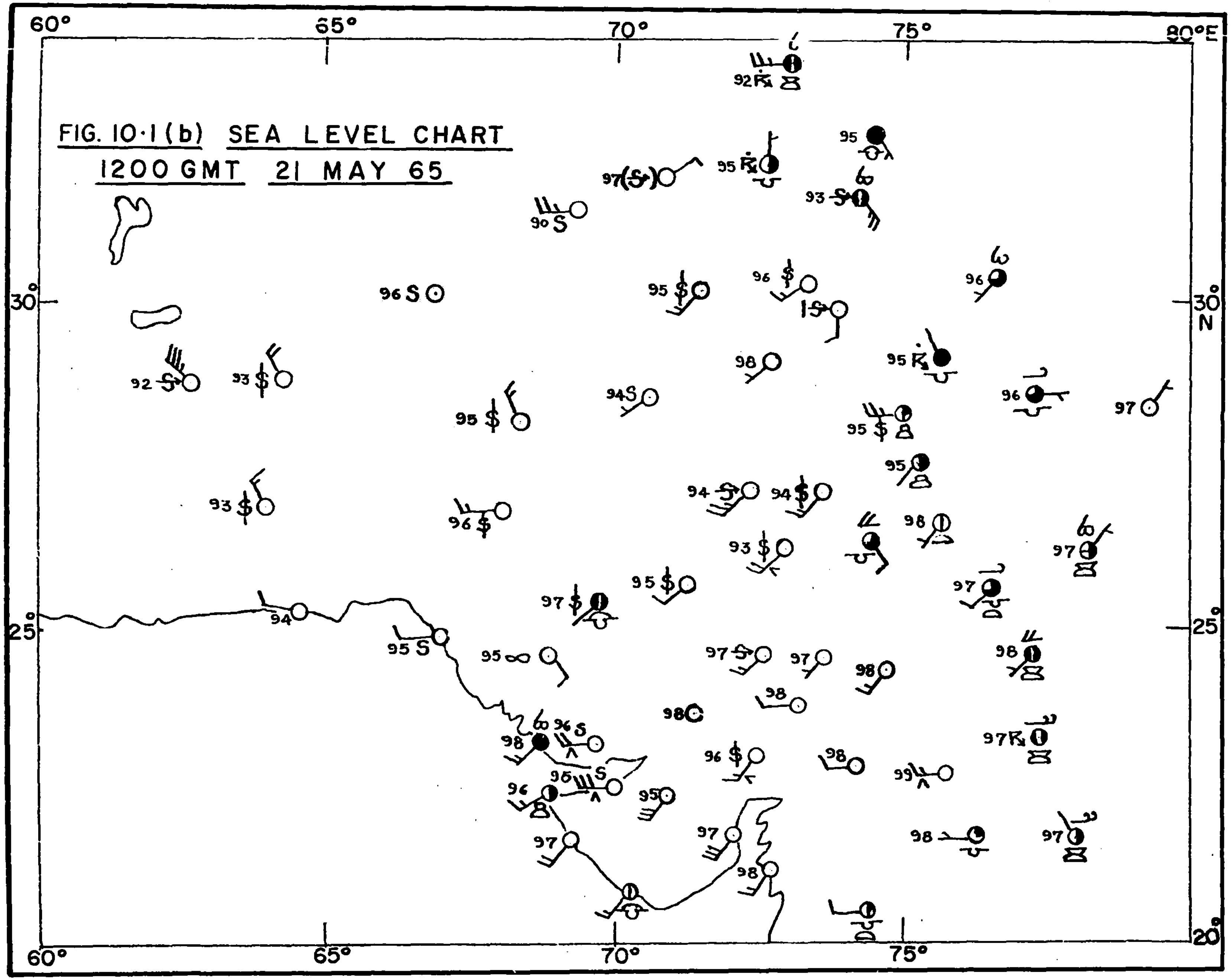
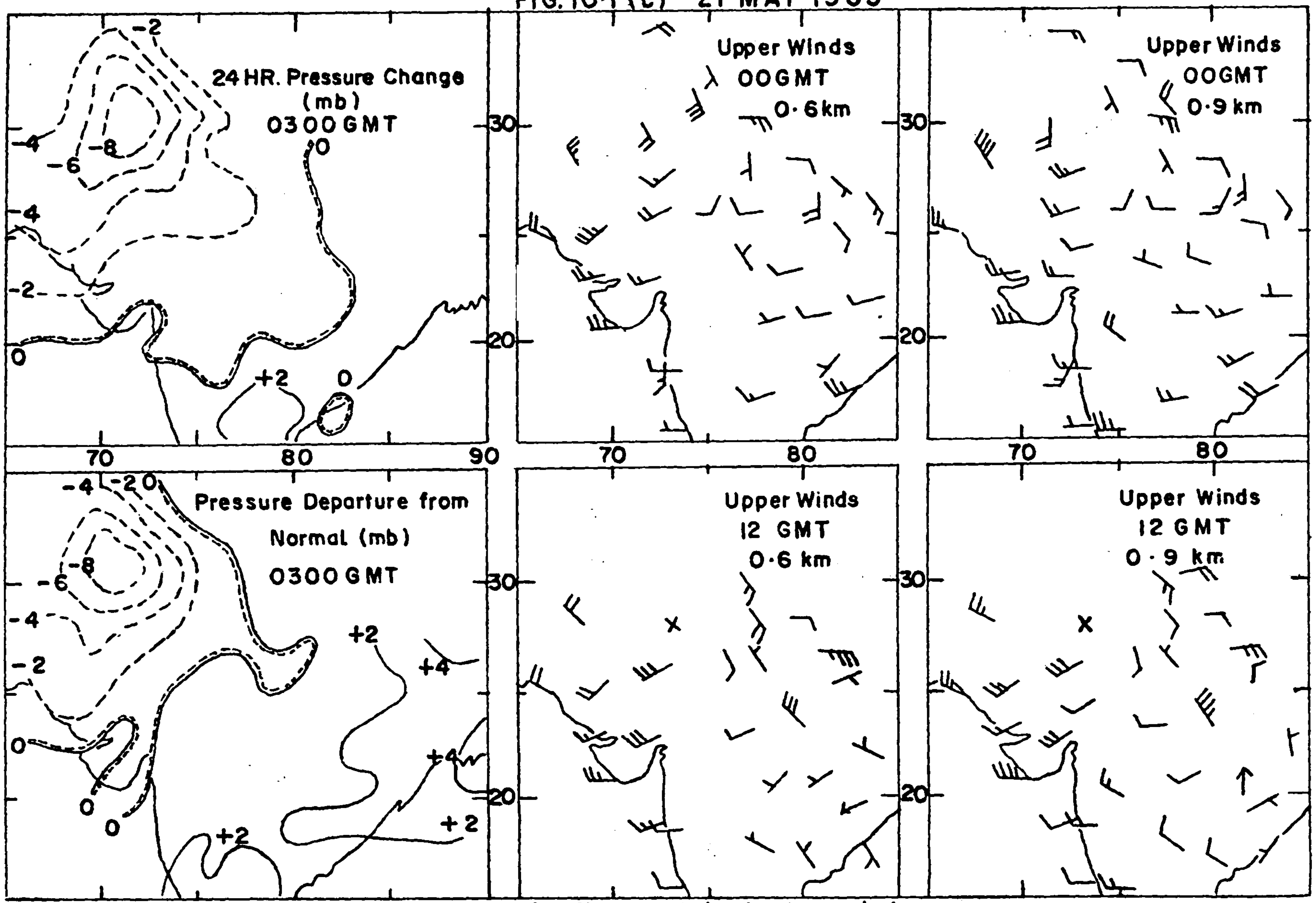


FIG. 10·1(b) SEA LEVEL CHART

1200 GMT 21 MAY 65

FIG. 10·1 (c) 21 MAY 1965



X···· No ascent due to strong wind

FIG.11.1 (a) CROSS SECTION ALONG LONGITUDE 75°E -27 FEB. 70 : 00 GMT

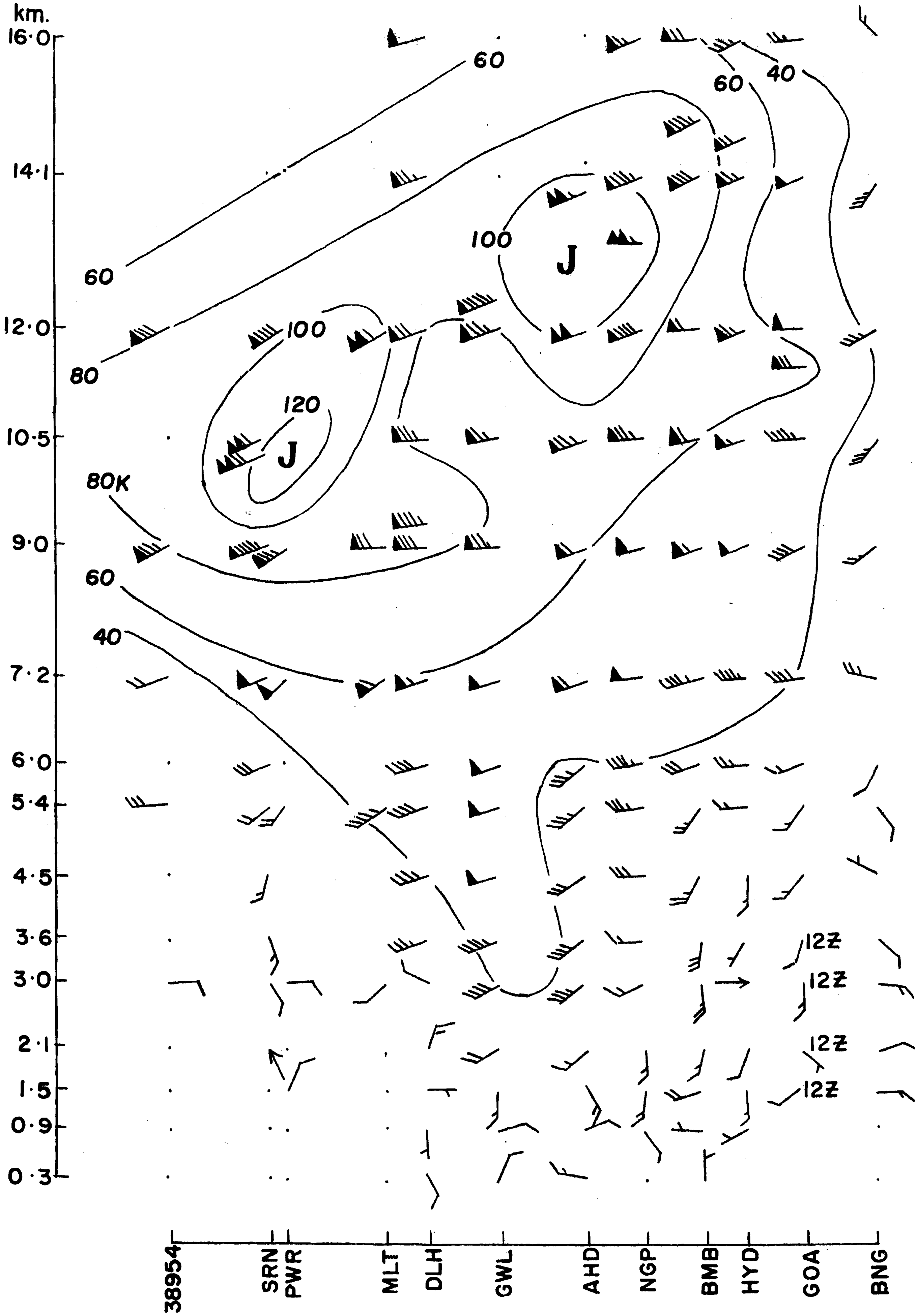
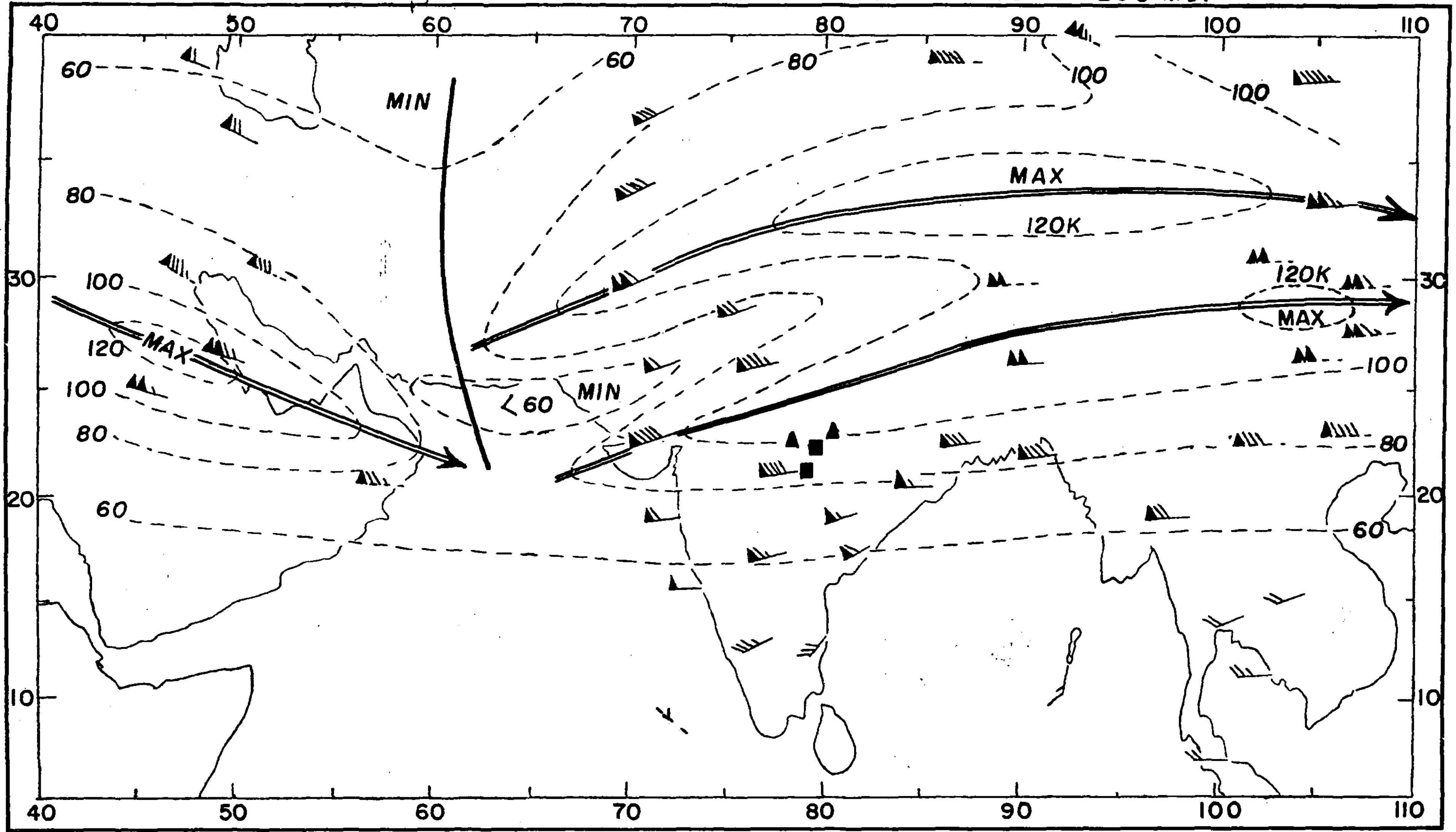


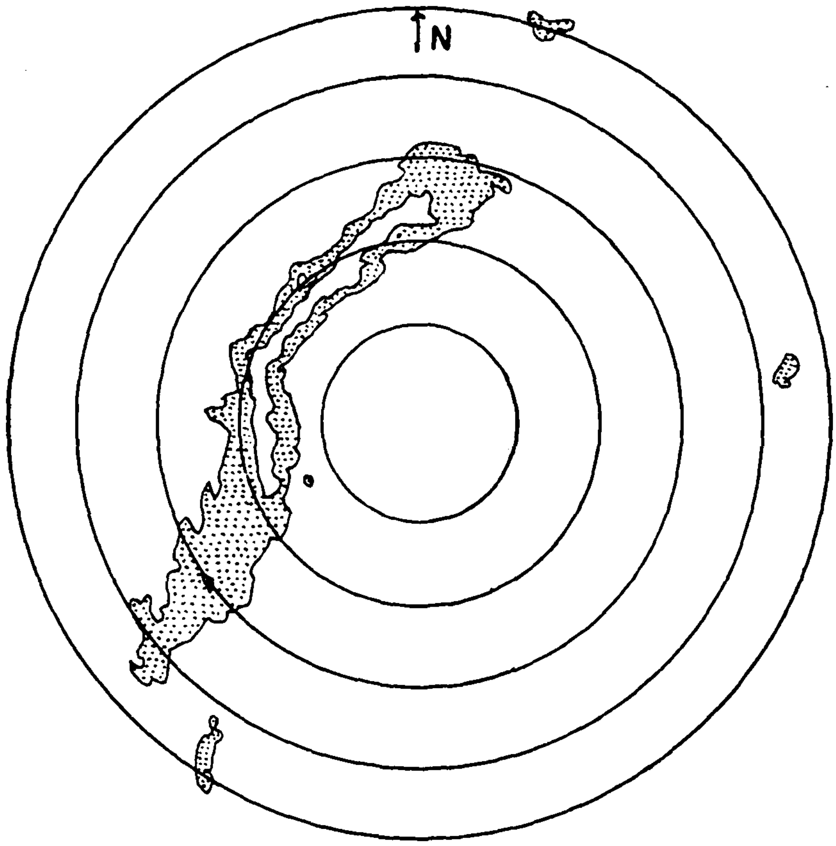
FIG. II·1 (b) UPPER WINDS 00 GMT 27 FEBRUARY 70 200 mb.



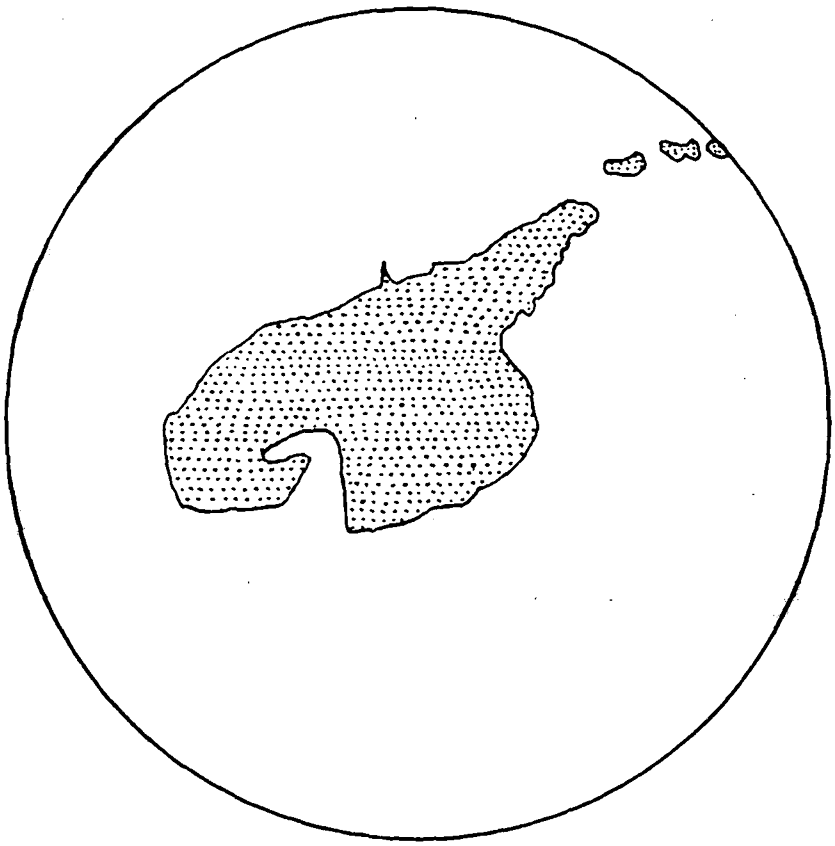
■ Places from where hail was reported on 27 Feb. 70 ▲ Places from where hail was reported on 28 Feb. 70

Trough line ------ Isotach in kts. ⟹ Jet Broken shaft indicates 12 GMT data.

FIG. 12·1 TYPICAL RADAR ECHOES



Radar Picture of Squall-line at 1630 IST on 17.4.1962 at Agartala.
(Reproduced from "A radar study of a squall-line at Agartala" by D.V. Subramanian, IJMG 1963 Vol.14 No.4 pp.447-452).



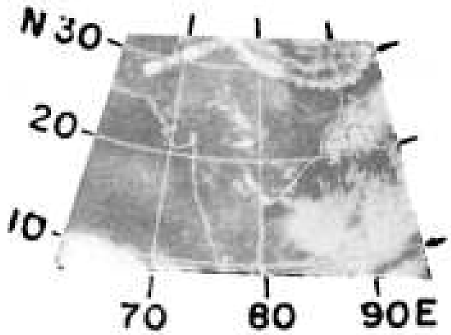
Typical Picture of a "Hook Type Echo"
Reproduced from "Weather Radar Manual"
(Interpretation of Echoes) IMD 1965.

FIG. 13·1

ESSA - 9   ORBIT 5583

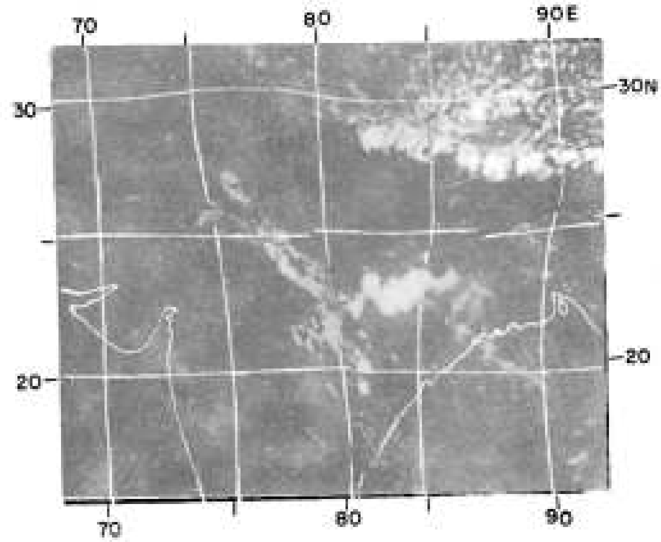
19 May 70   0707 GMT

Copied from "Catalog of Meteorological Satellite Data ESSA-9 & ITOS-1 Television Cloud Photography" (NOAA Publication KMRD No 5·326

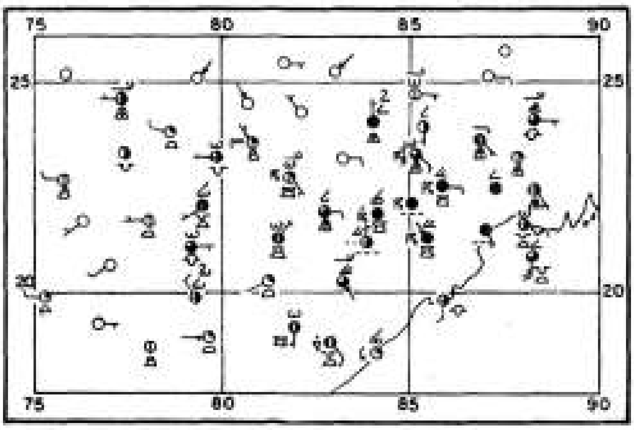


ITOS-1   ORBIT 1451, 1450

19 May 70   1037, 0834 GMT



CLOUD DISTRIBUTION AT 1200 GMT OF 19 MAY 70



PAST WEATHER & RAINFALL 1200 GMT 19 MAY 70

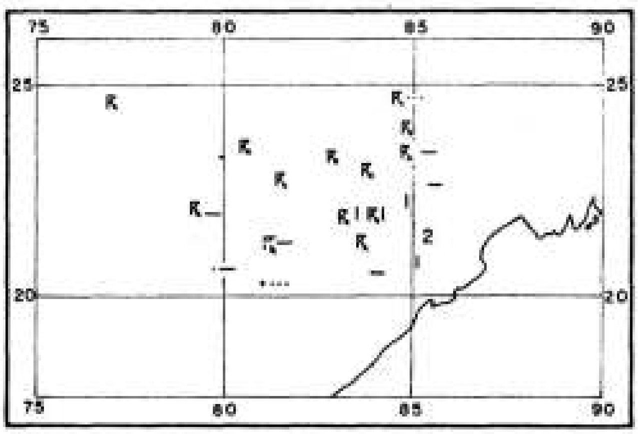
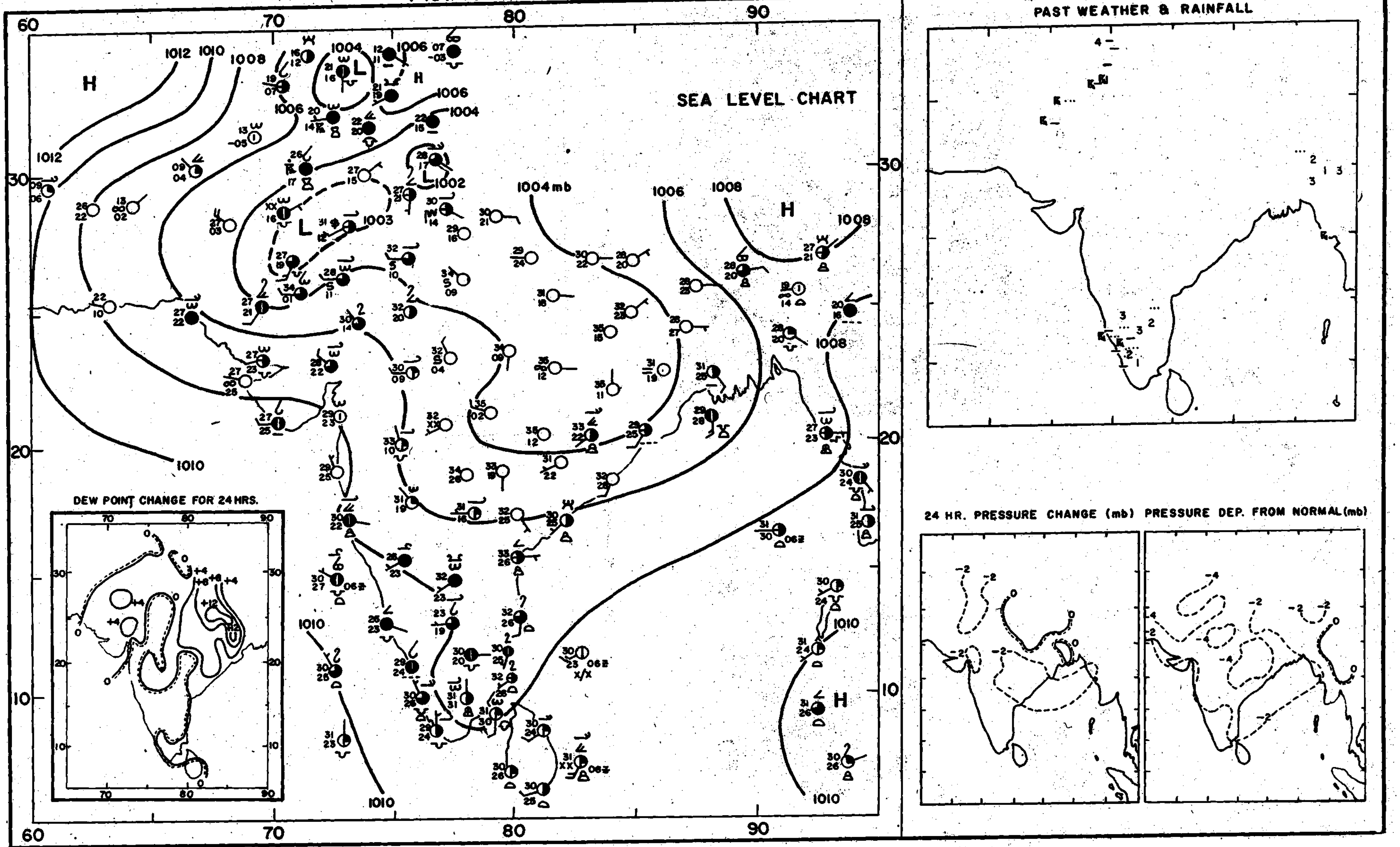
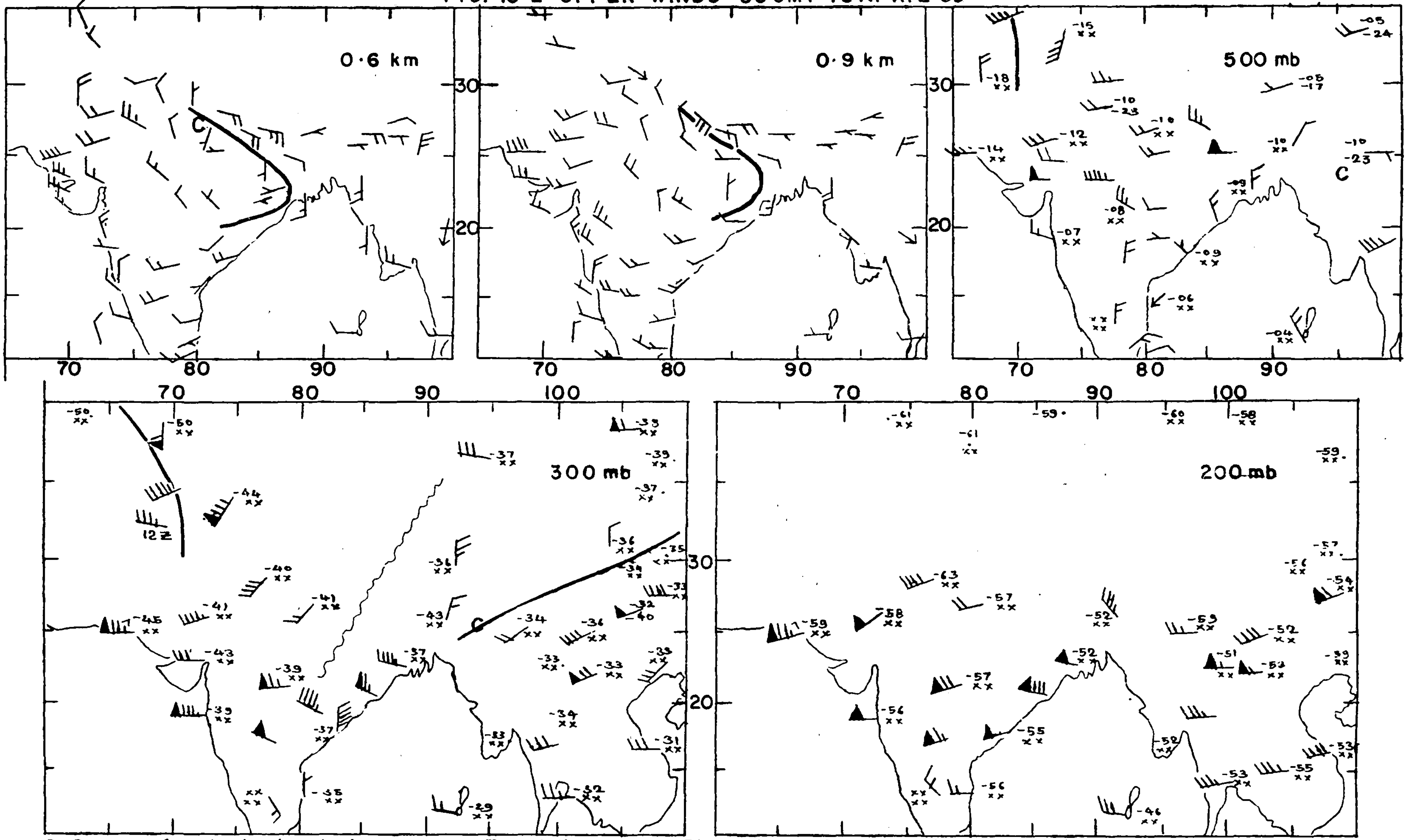


FIG. 15·1 SYNOPTIC CHARTS 0300 GMT 16 APR. 69



Note – Figures to the left of the station circle refer to Dry bulb and Dew point temperatures.

FIG. 15·2 UPPER WINDS 00GMT 16 APRIL 69



C-Centre of cyclonic circulation —— Trough line ~~~ Ridge line Plotted figures TT & T_dT_d

FIG. 15·3 SYNOPTIC CHARTS 0300GMT 17APR.69

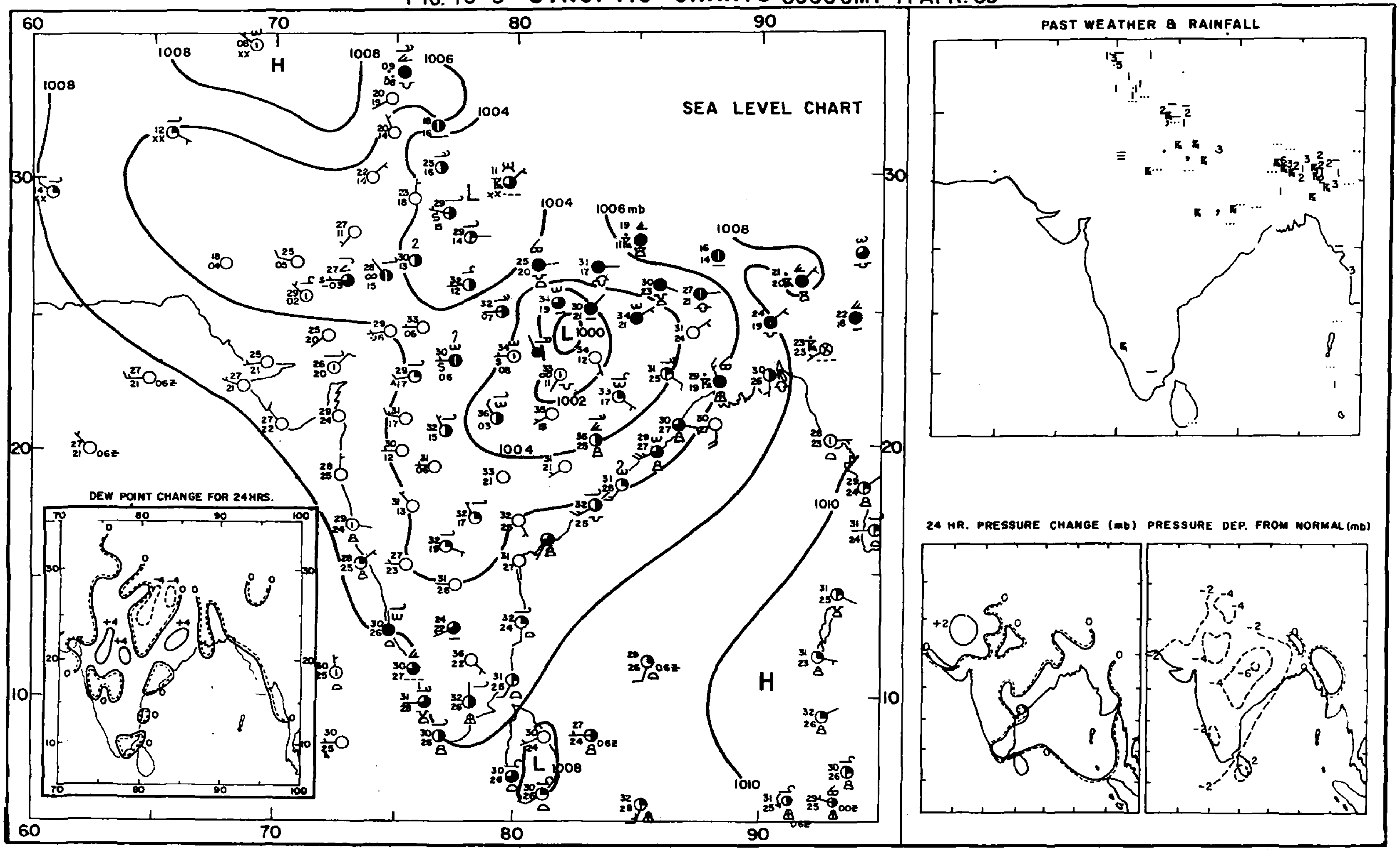
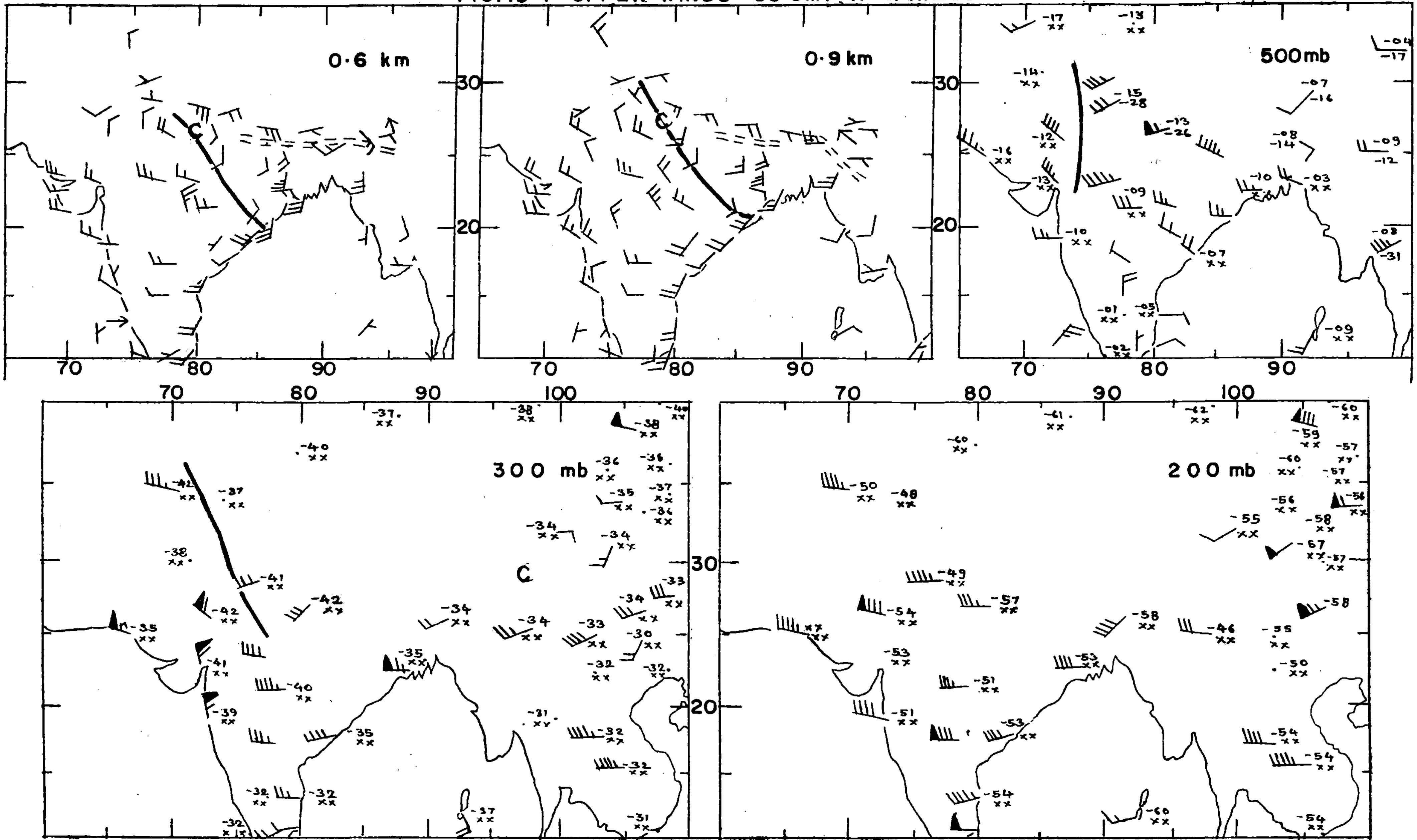


FIG. 15·4 UPPER WINDS 00 GMT 17 APRIL 69



C - Centre of cyclonic circulation ===== Wind discontinuity ━━ Trough line Plotted figures T T & T_dT_d

FIG. 15·5 TEPHIGRAMS OF CALCUTTA 17 APRIL 1969

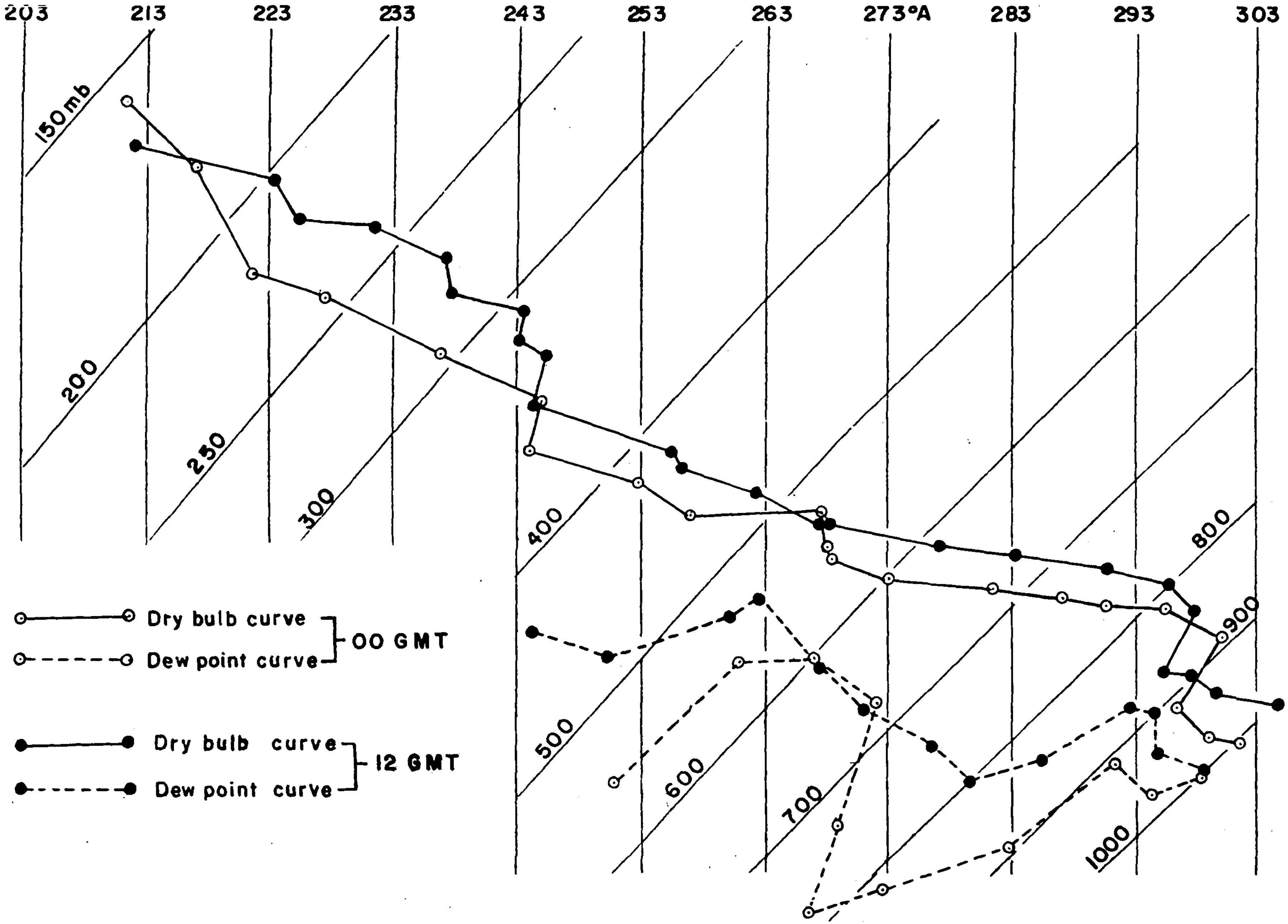
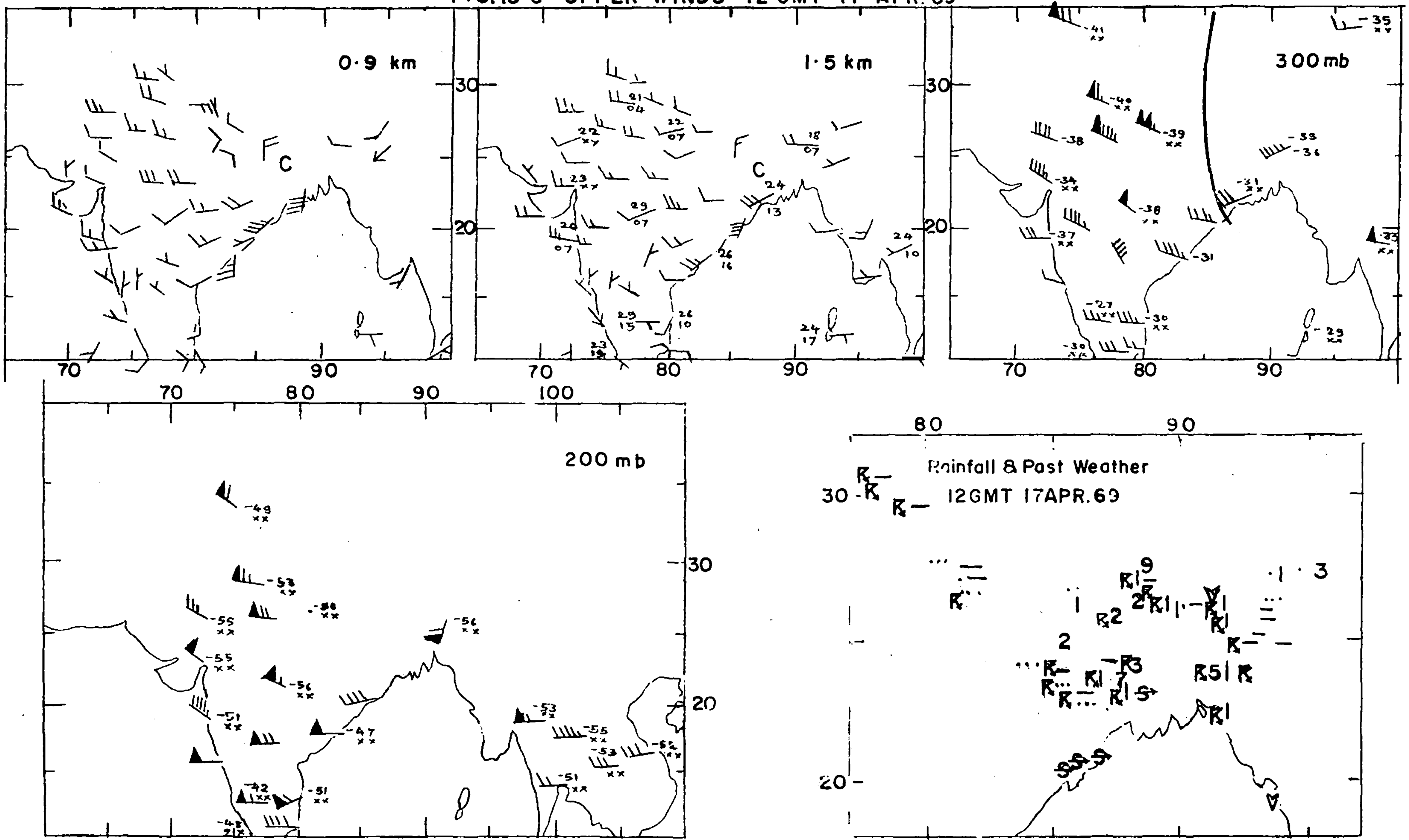


FIG. 15·6 UPPER WINDS 12 GMT 17 APR. 69



C - Centre of cyclonic circulation ——— Trough line Plotted figures TT & T_dT_d ∇ Squall

FIG. 15·7 **SYNOPTIC CHARTS** 03 GMT 18 APR. 69

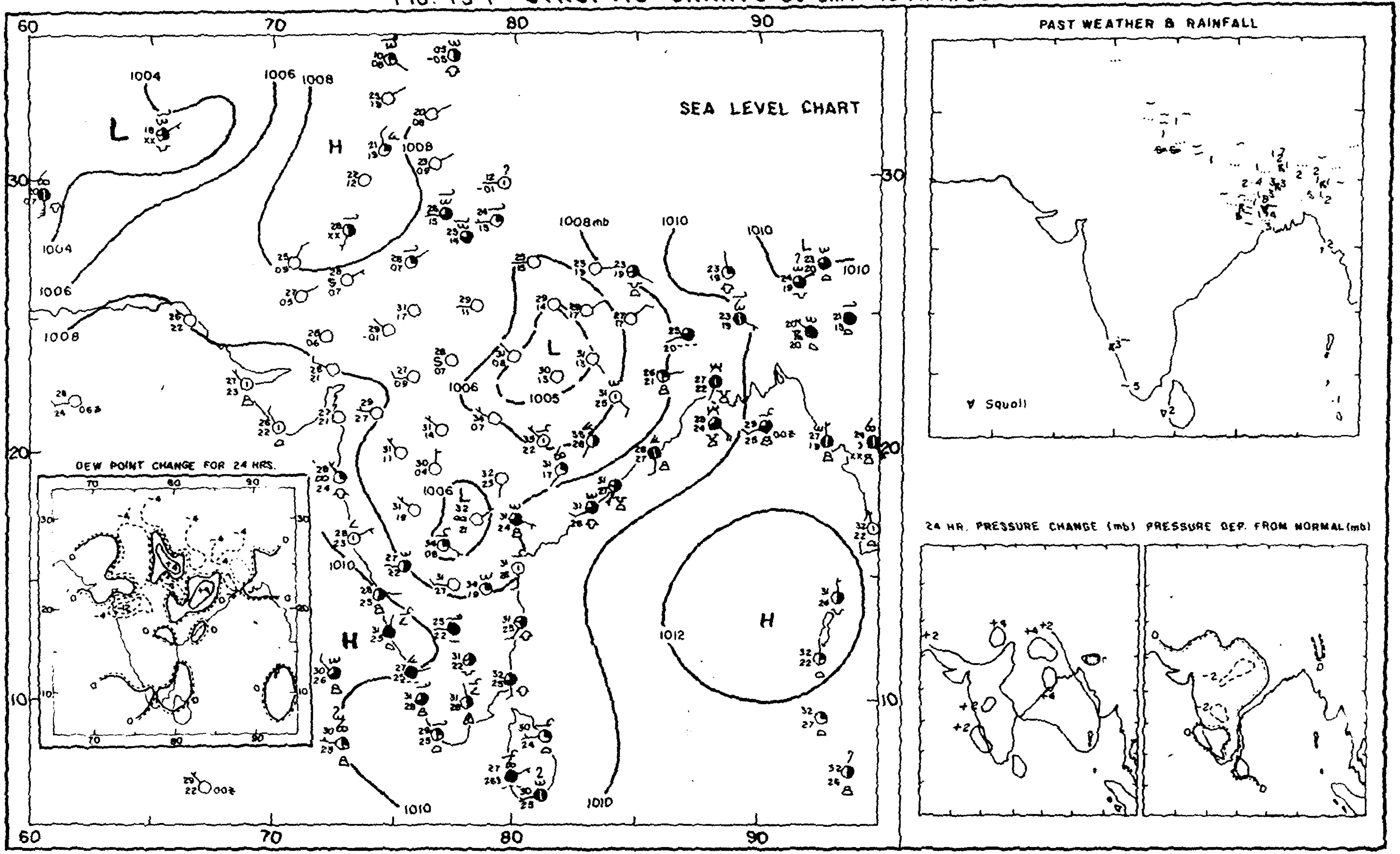
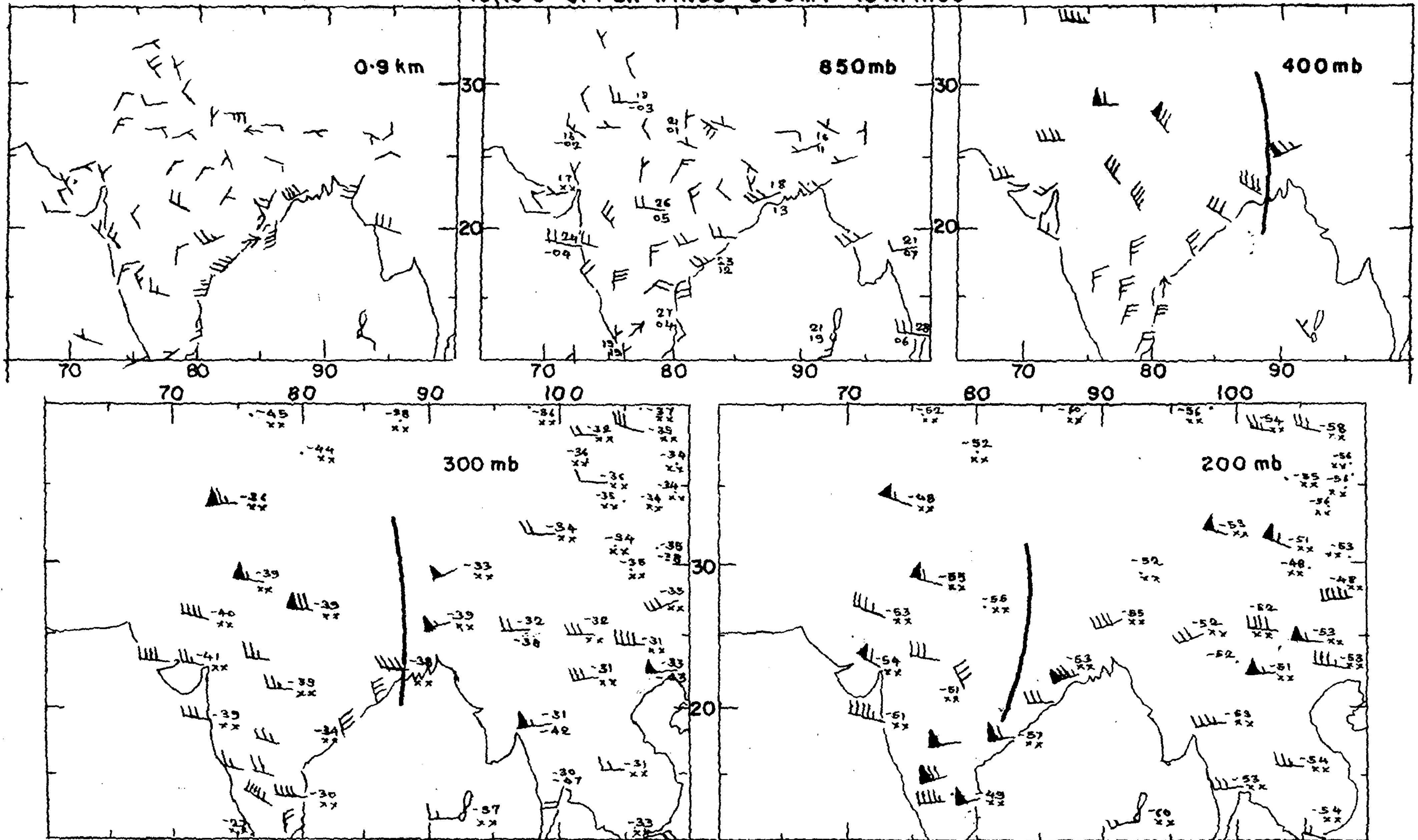


FIG. 15·8 UPPER WINDS 00GMT 18 APR. 69



Trough line   Plotted figures TT & T_dT_d

FIG. 15·9 VERTICAL TIME SECTION FOR CALCUTTA : 15-20 APRIL 69

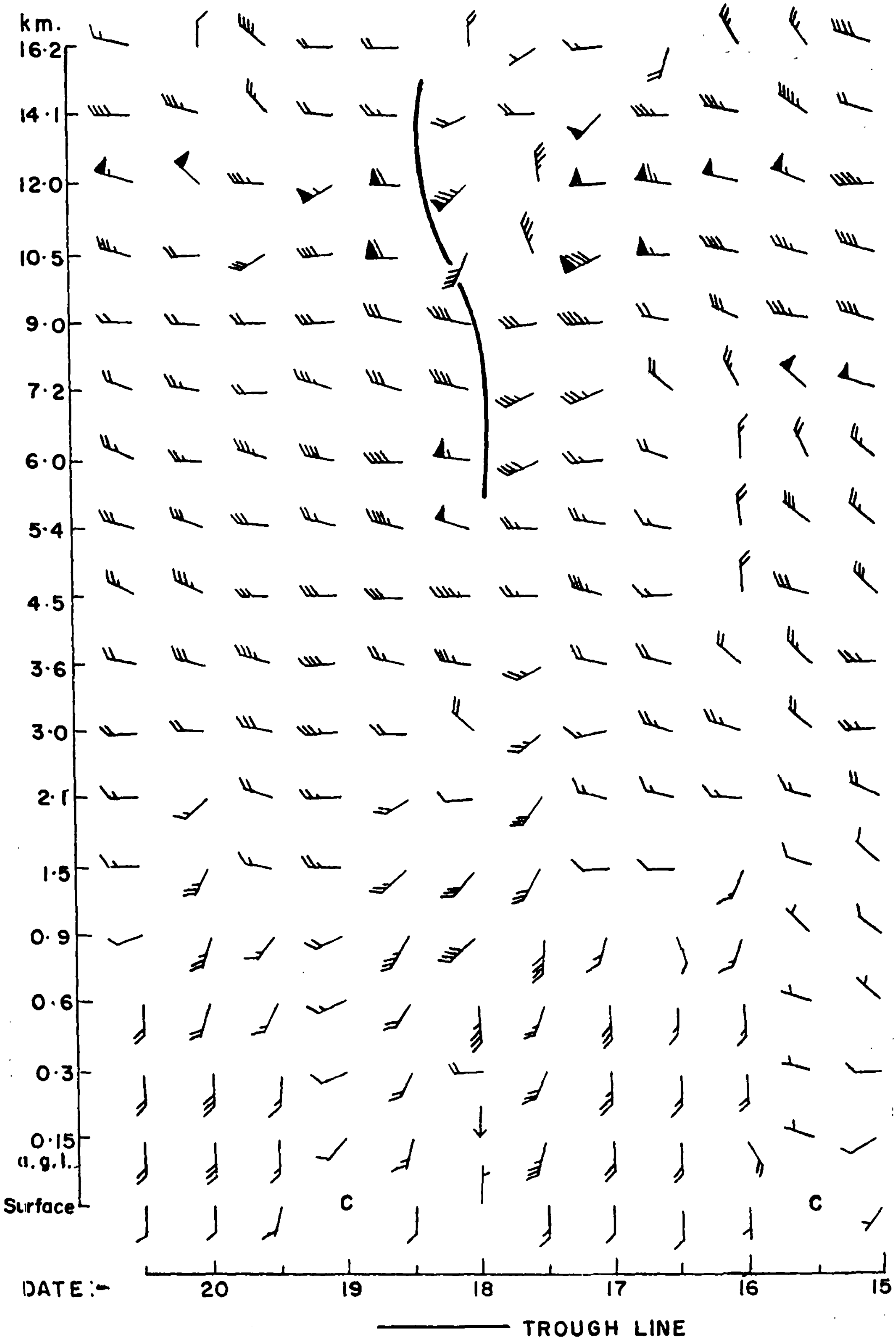
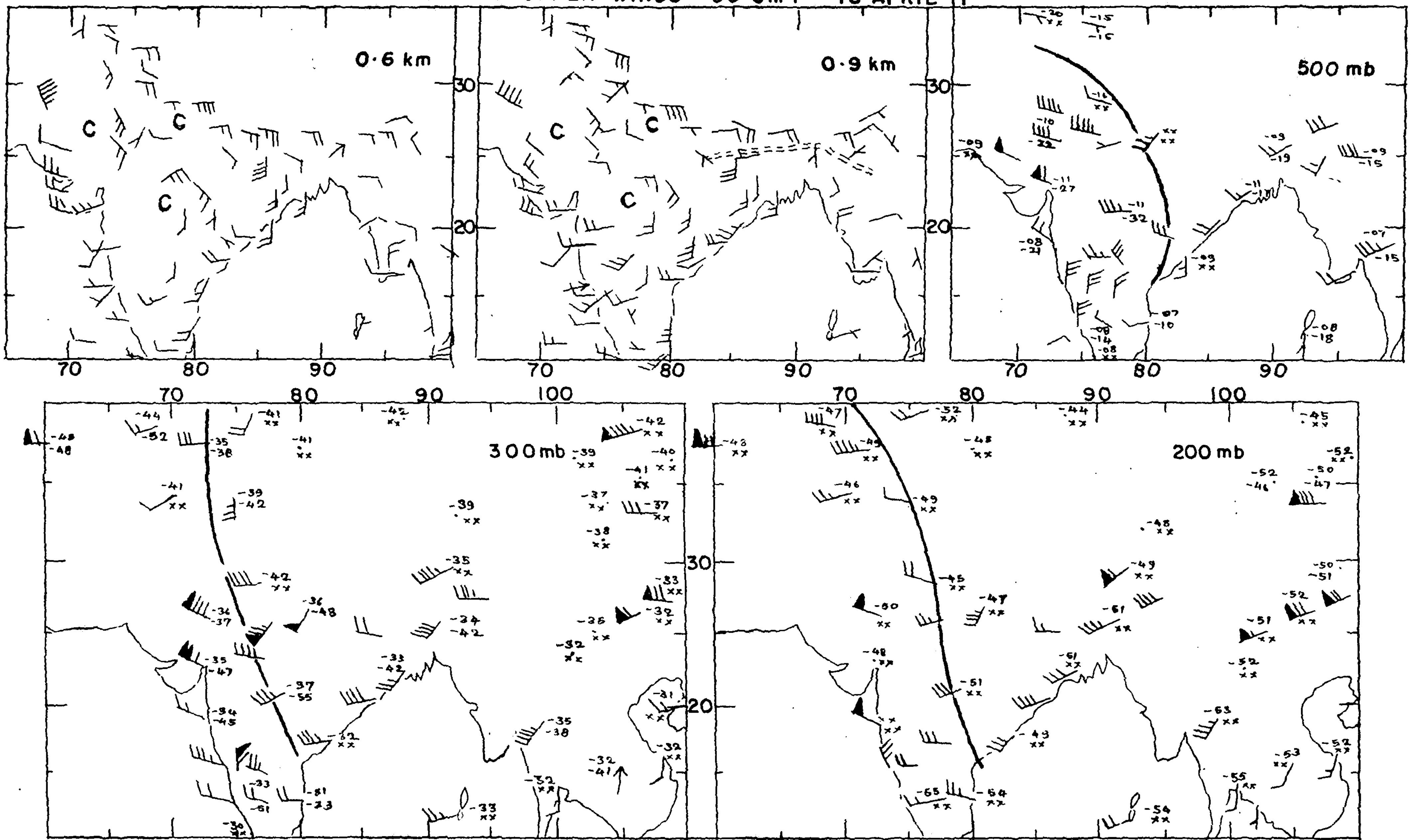


FIG. 16·2·1 UPPER WINDS 00 GMT 18 APRIL 71



C- Centre of cyclonic circulation ===== Wind discontinuity ——— Trough line Plotted figures TT & T_dT_d

FIG. 16·2·2 **SYNOPTIC CHARTS** 0300 GMT 18 APR. 71

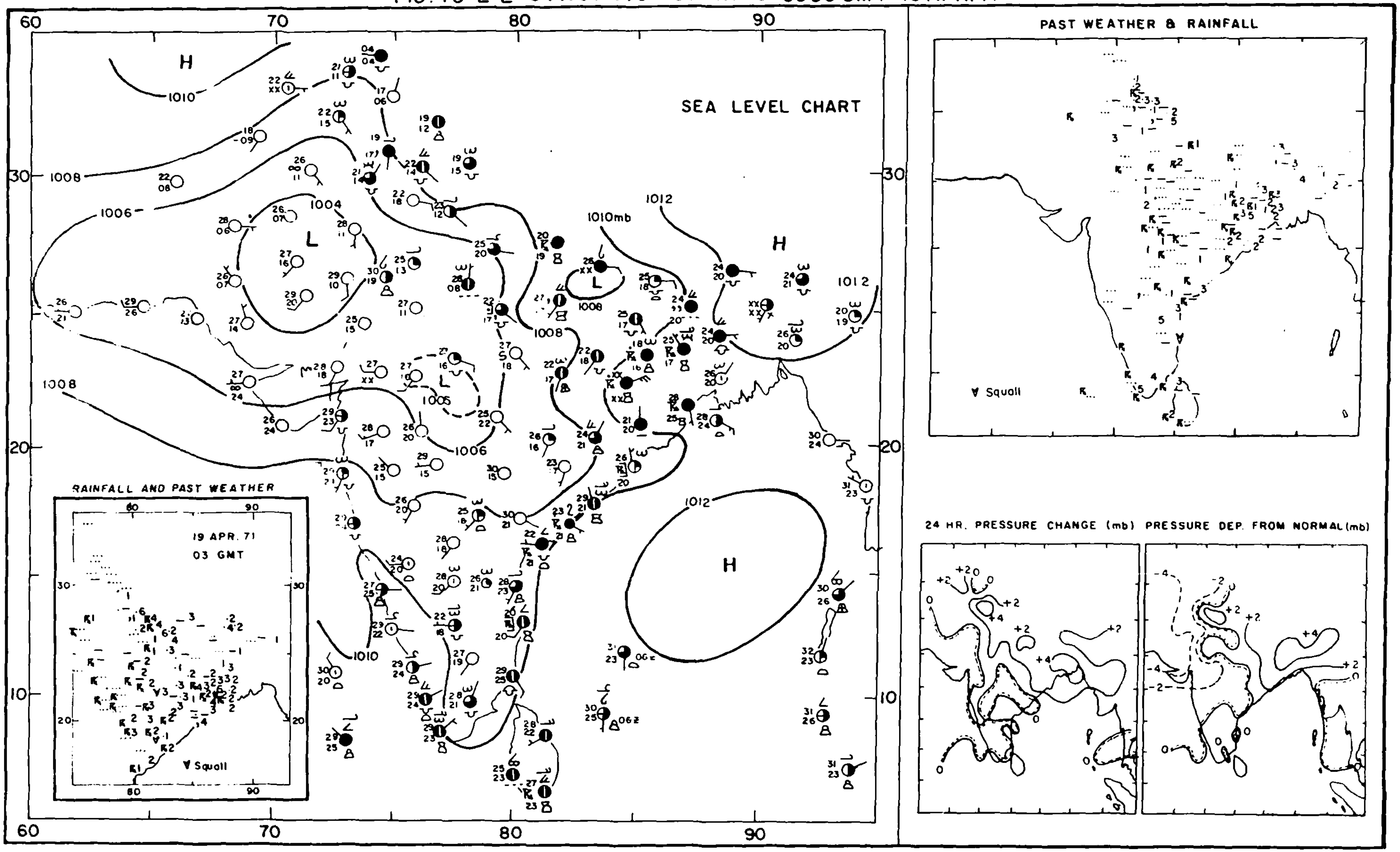


FIG. 16·2·3 CALCUTTA TEPHIGRAM 00 GMT 18 APRIL 1971

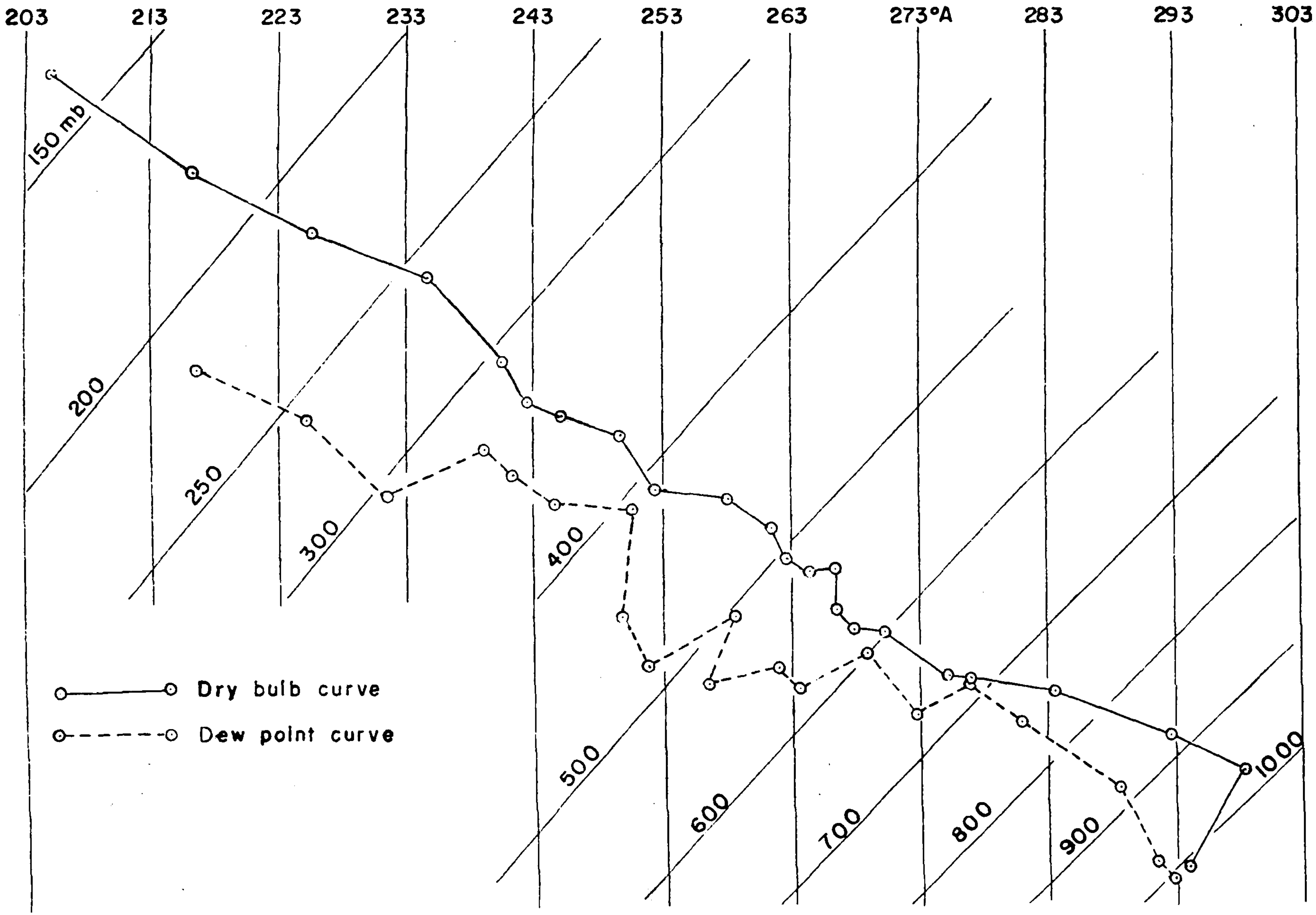
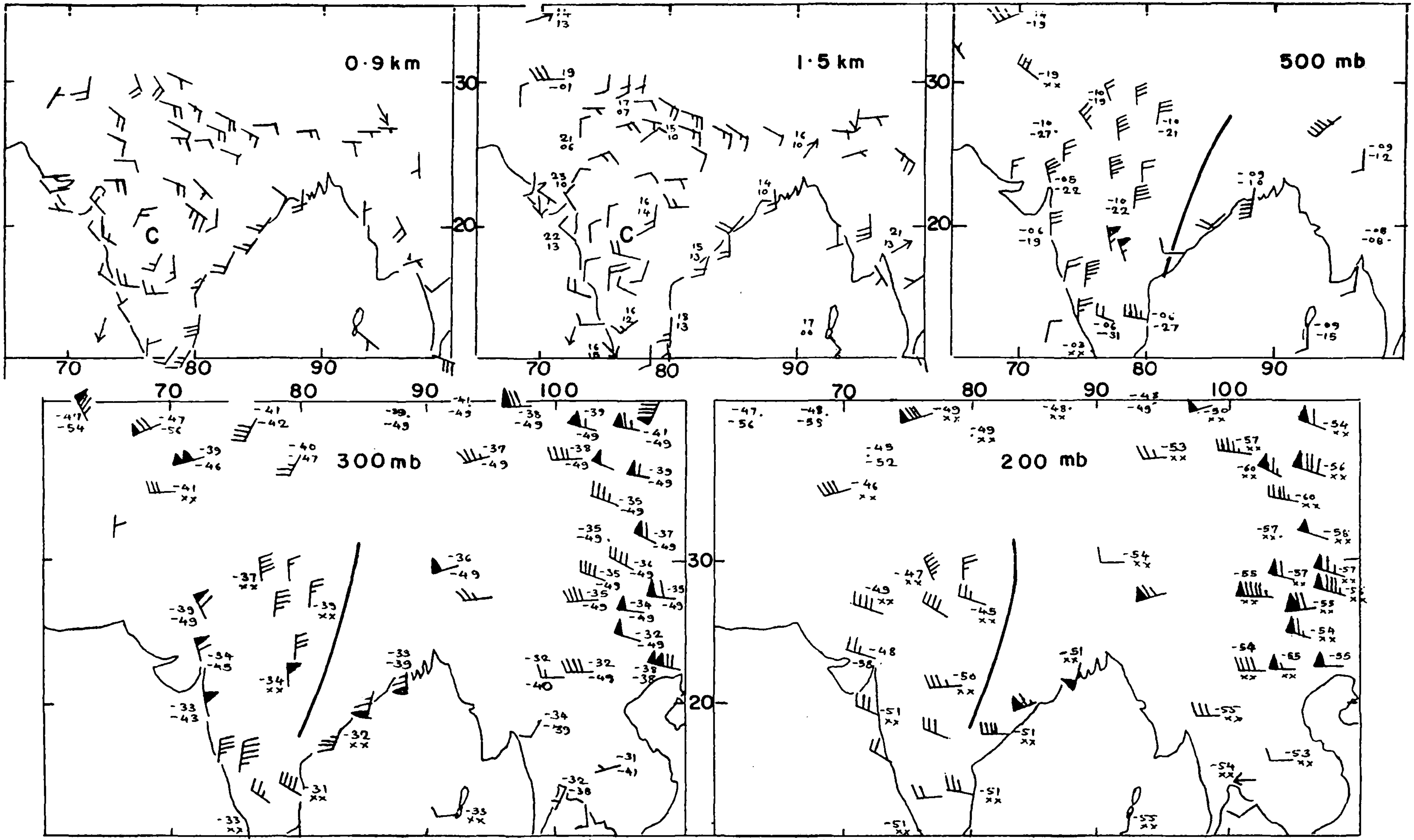
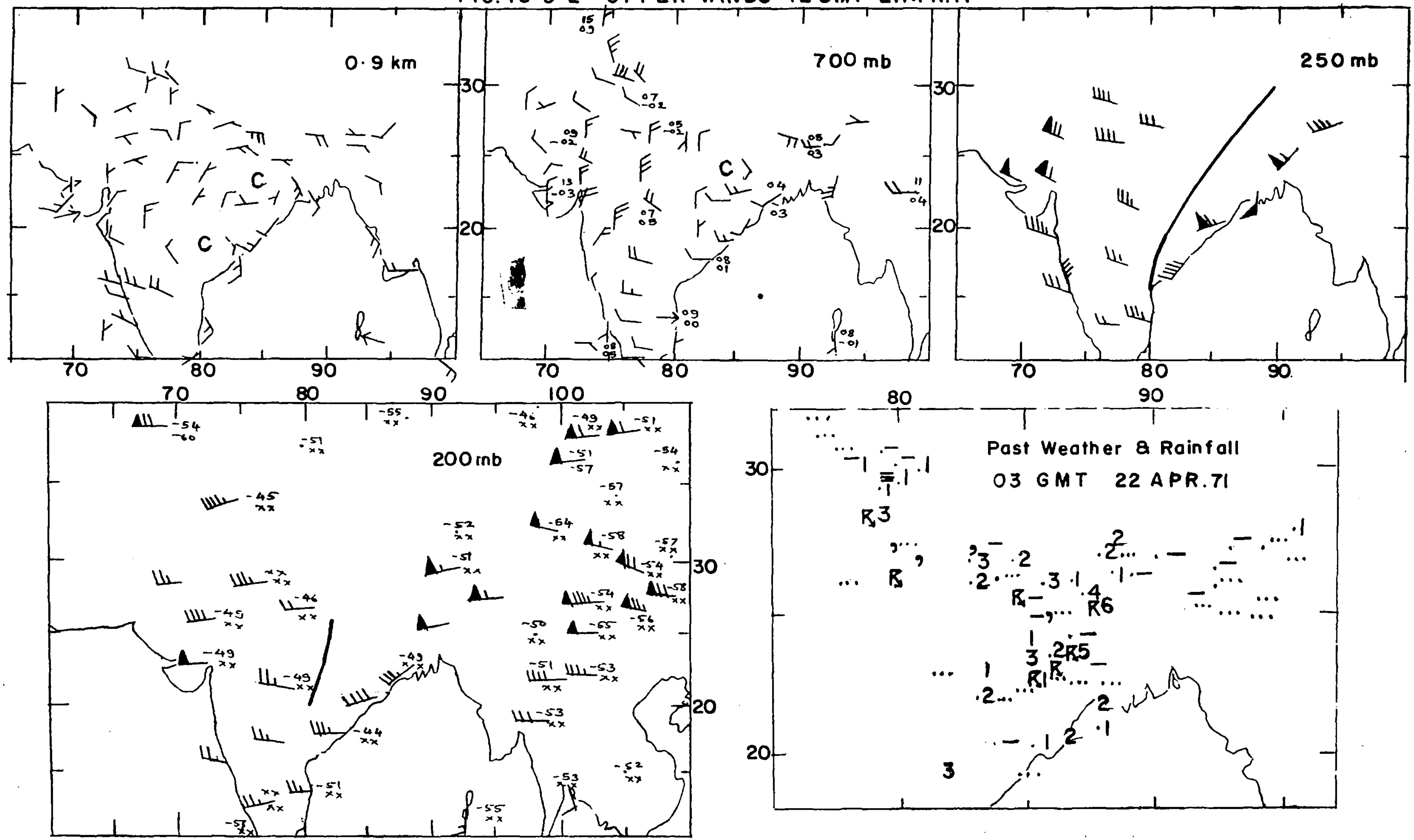


FIG. 16·3·1 UPPER WINDS OOGMT 21 APR.71



C-Centre of cyclonic circulation —— Trough line Plotted figures TT & $T_d T_d$

FIG. 16·3·2 UPPER WINDS 12 GMT 21 APR. 71



C - Centre of cyclonic circulation ——— Trough line Plotted figures TT & T_dT_d

FIG. 16·3·3 CALCUTTA TEPHIGRAMS 21 APRIL 1971

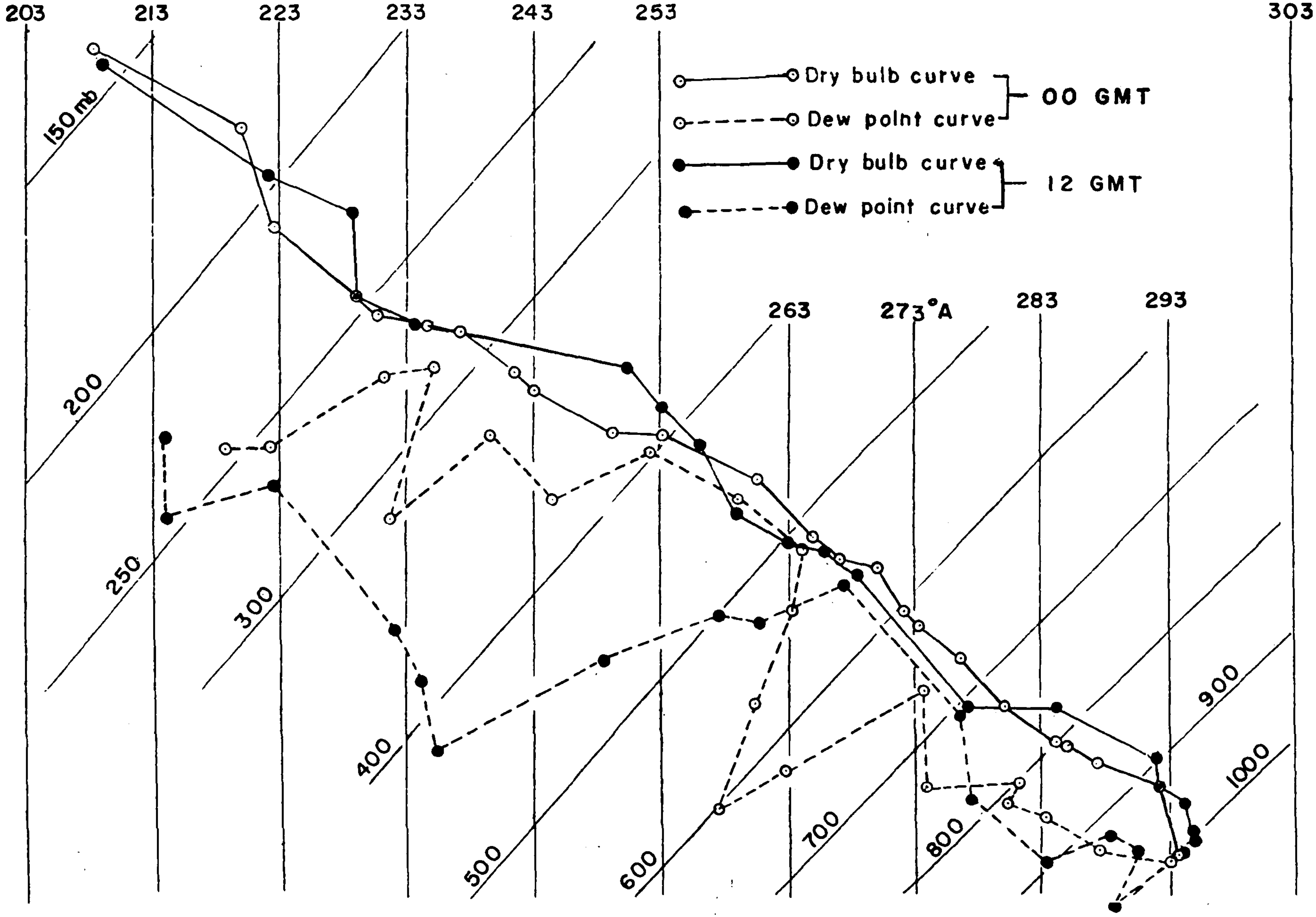


FIG. 16·3·4 (a) 17 APRIL 71 500mb

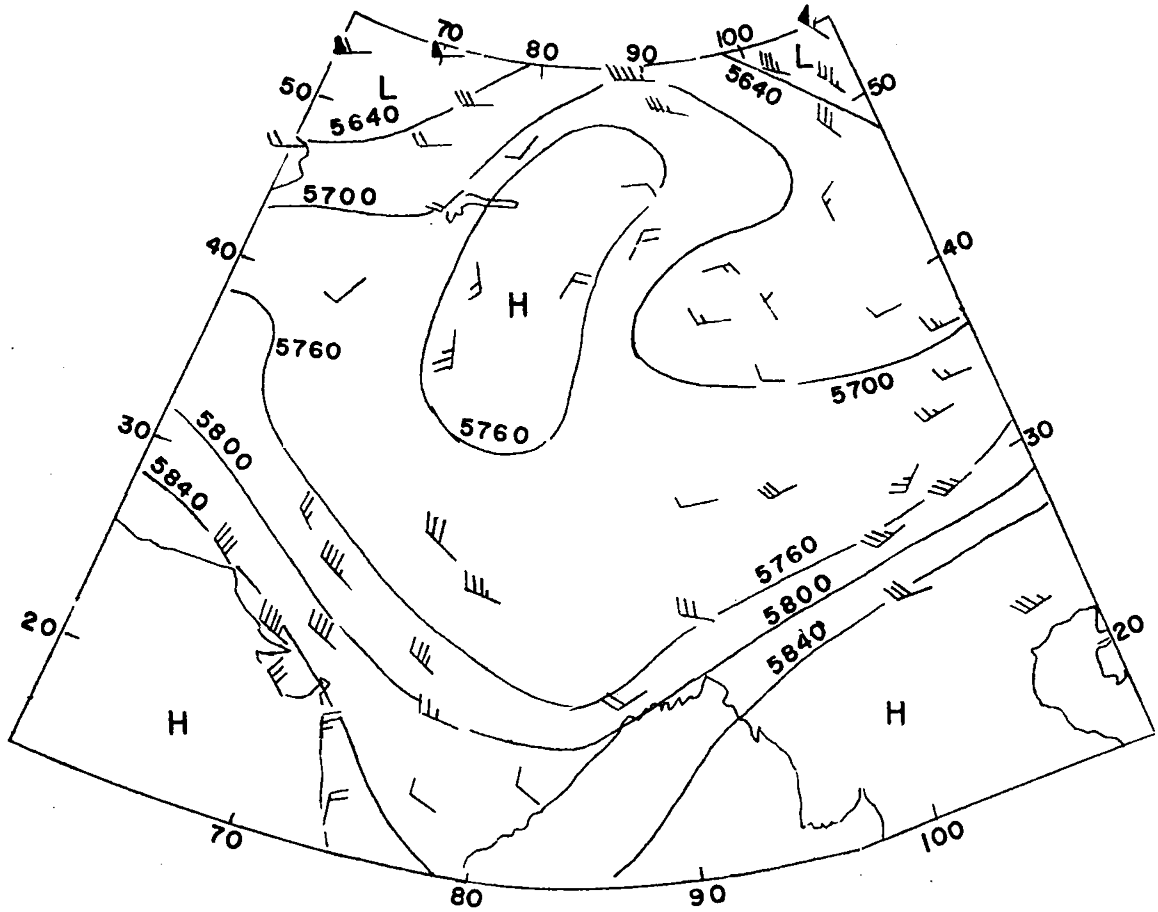
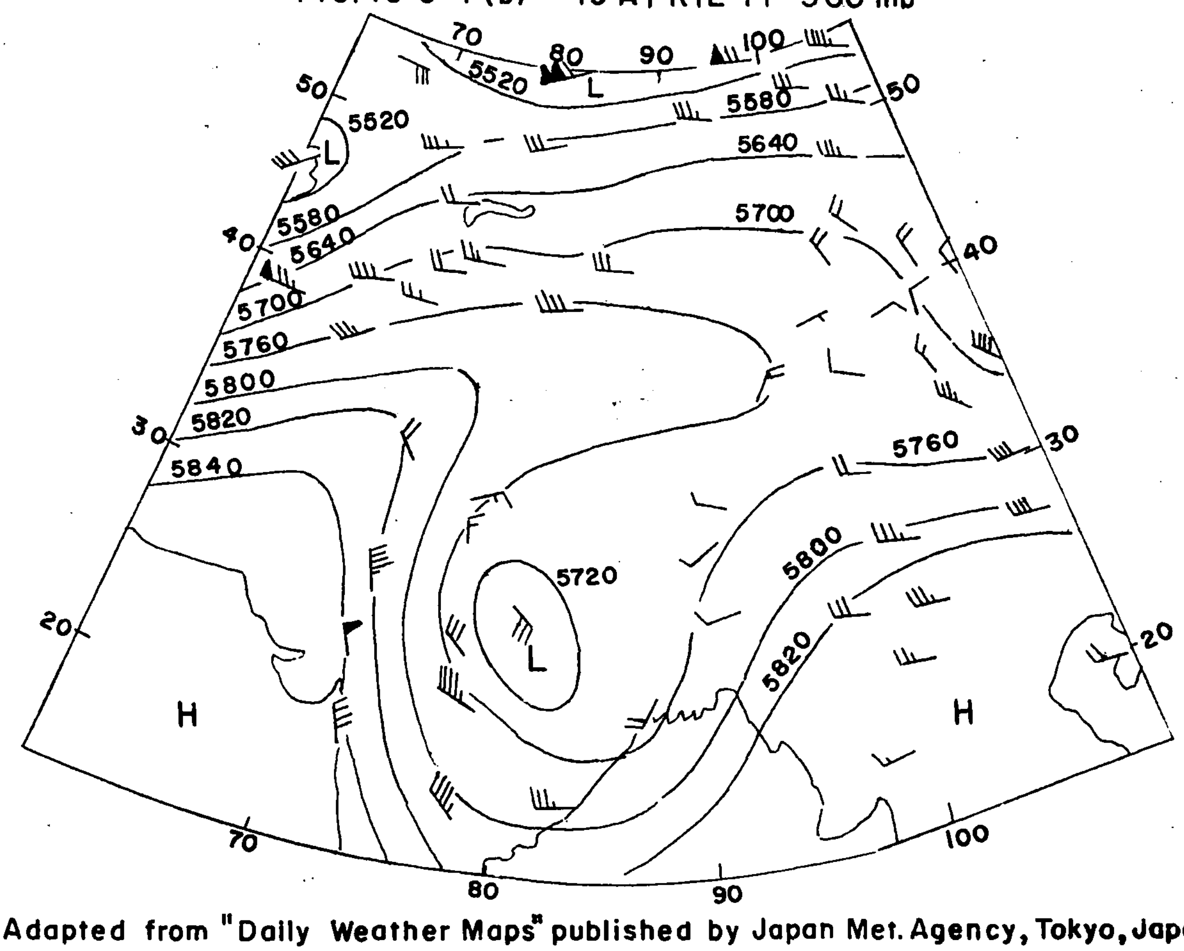
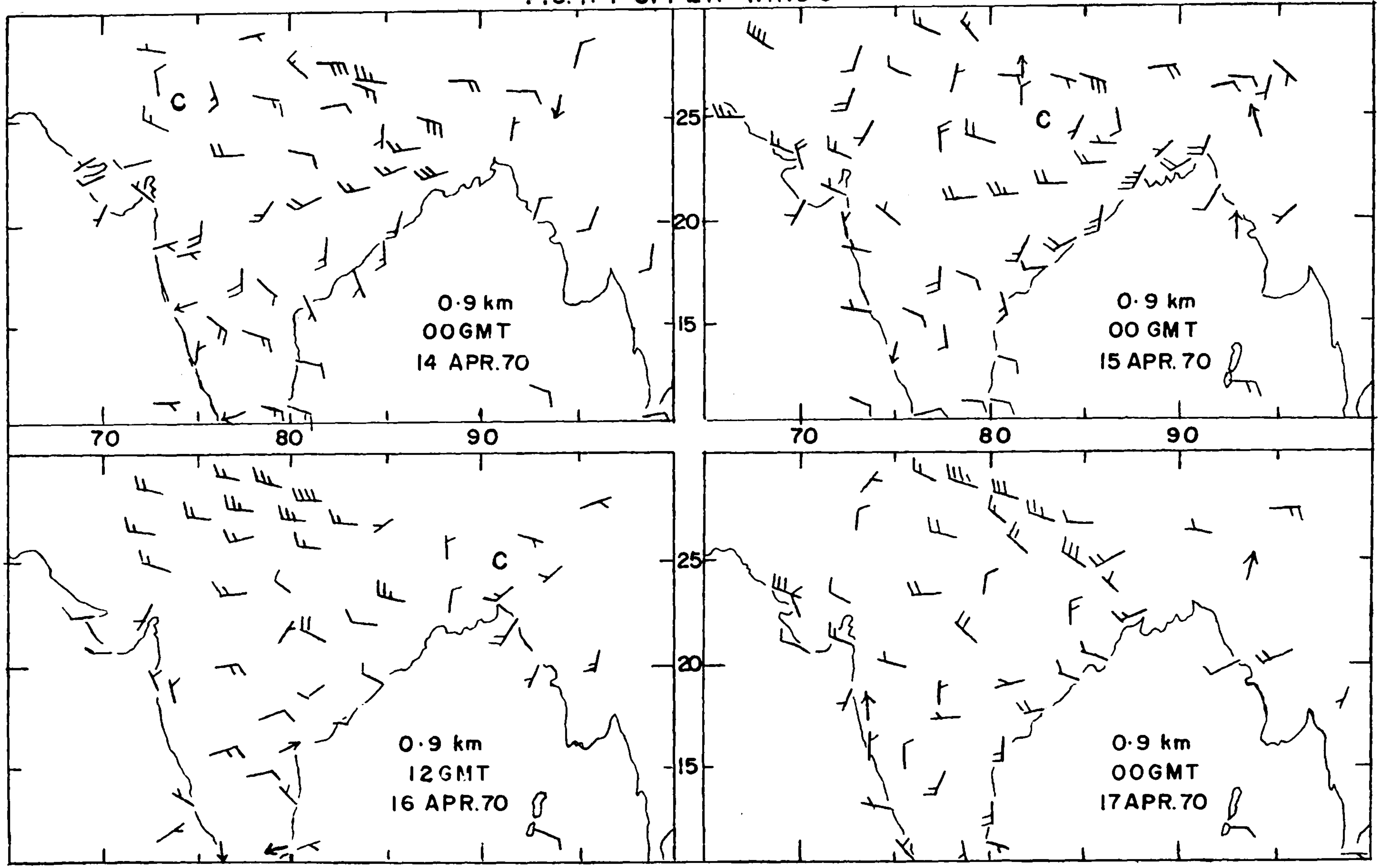


FIG. 16·3·4 (b) 19 APRIL 71 500 mb



Adapted from "Daily Weather Maps" published by Japan Met. Agency, Tokyo, Japan.

FIG. 17·1 UPPER WINDS



C- Centre of cyclonic circulation

FIG. 17·2 **SYNOPTIC CHARTS** 0300 GMT 16 APR. 70

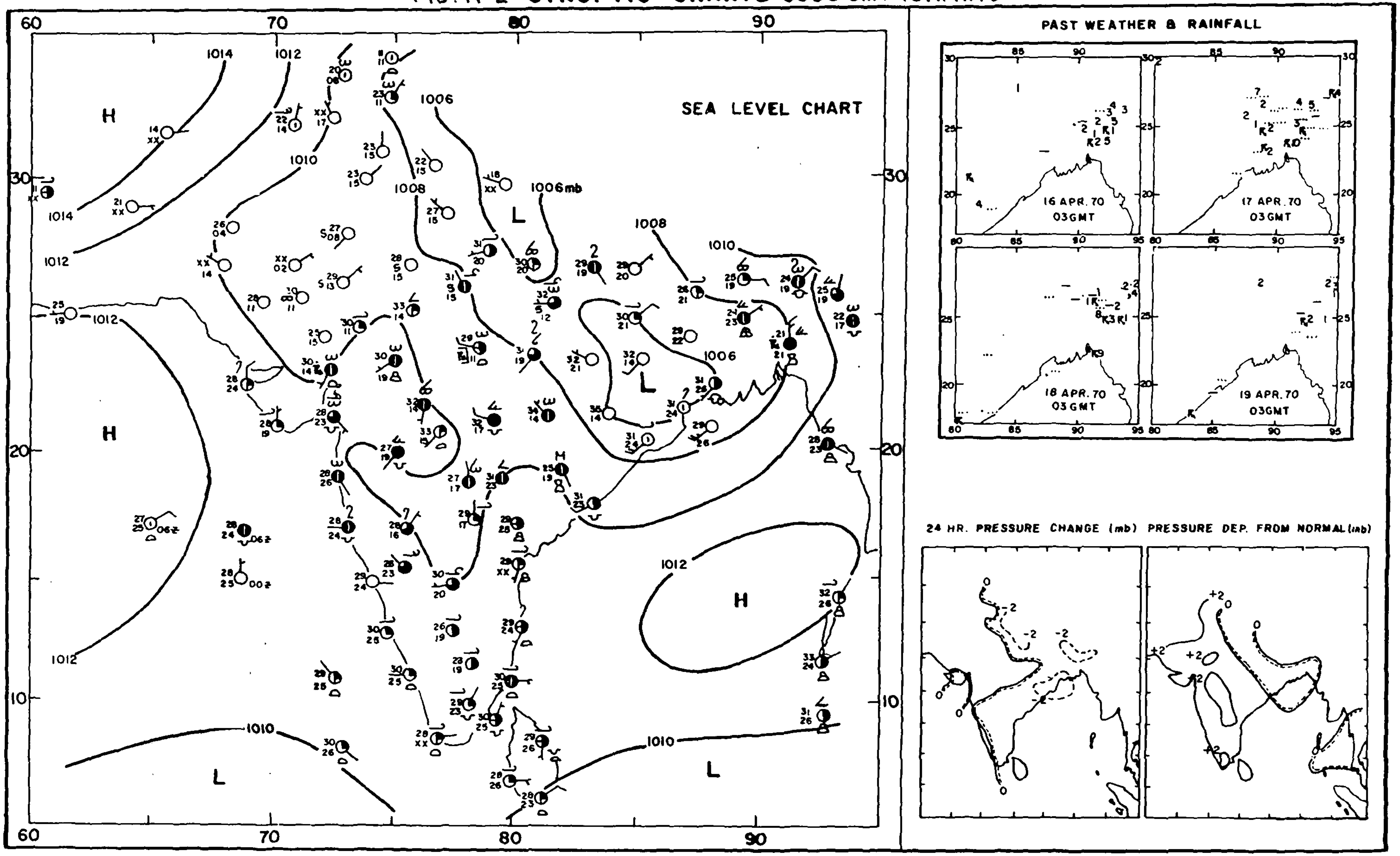


FIG. 17·3 TEPHIGRAM OF GAUHATI 00 GMT 15 APRIL 1970

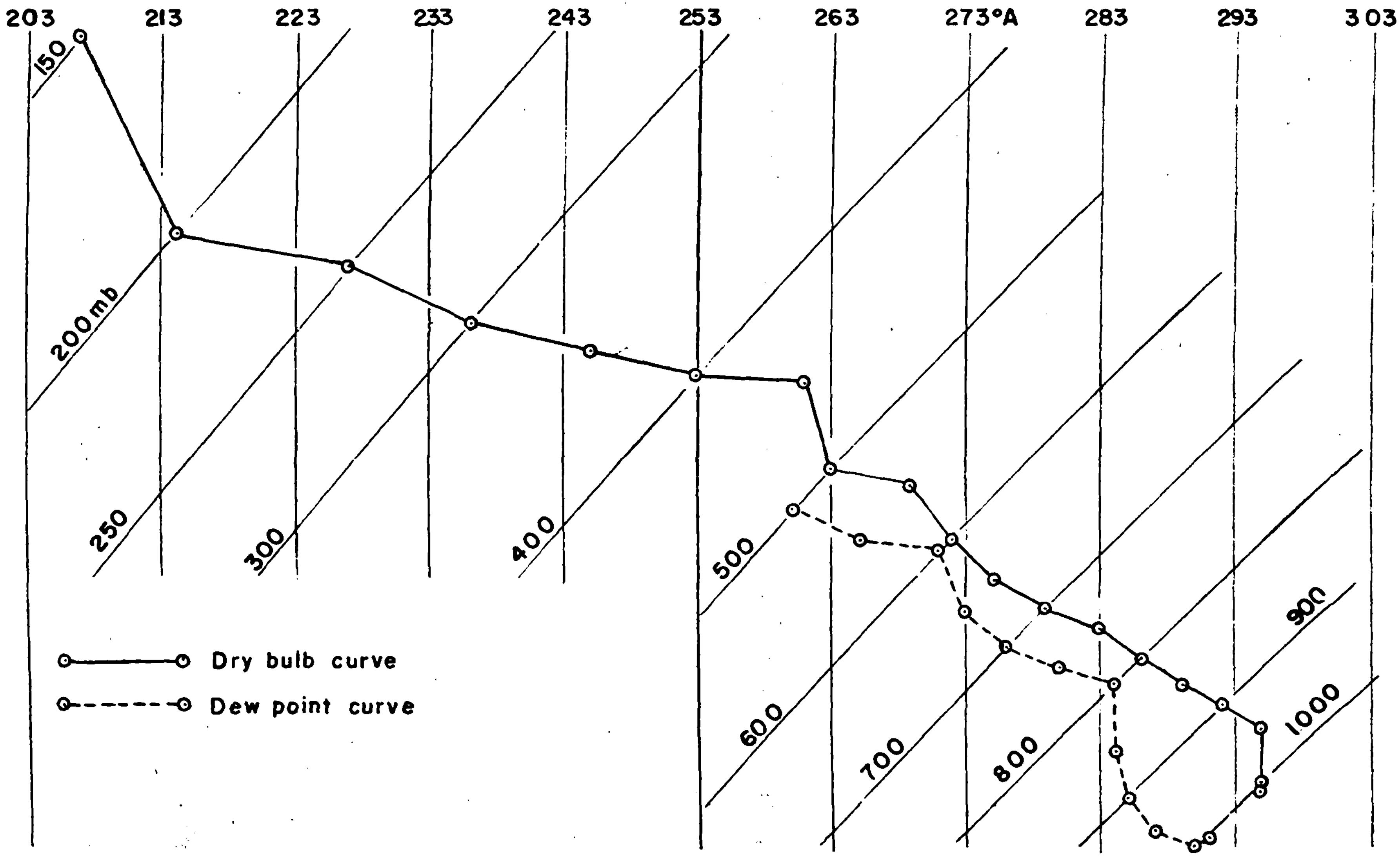


FIG. 17·4 UPPER WINDS 200mb 00 GMT

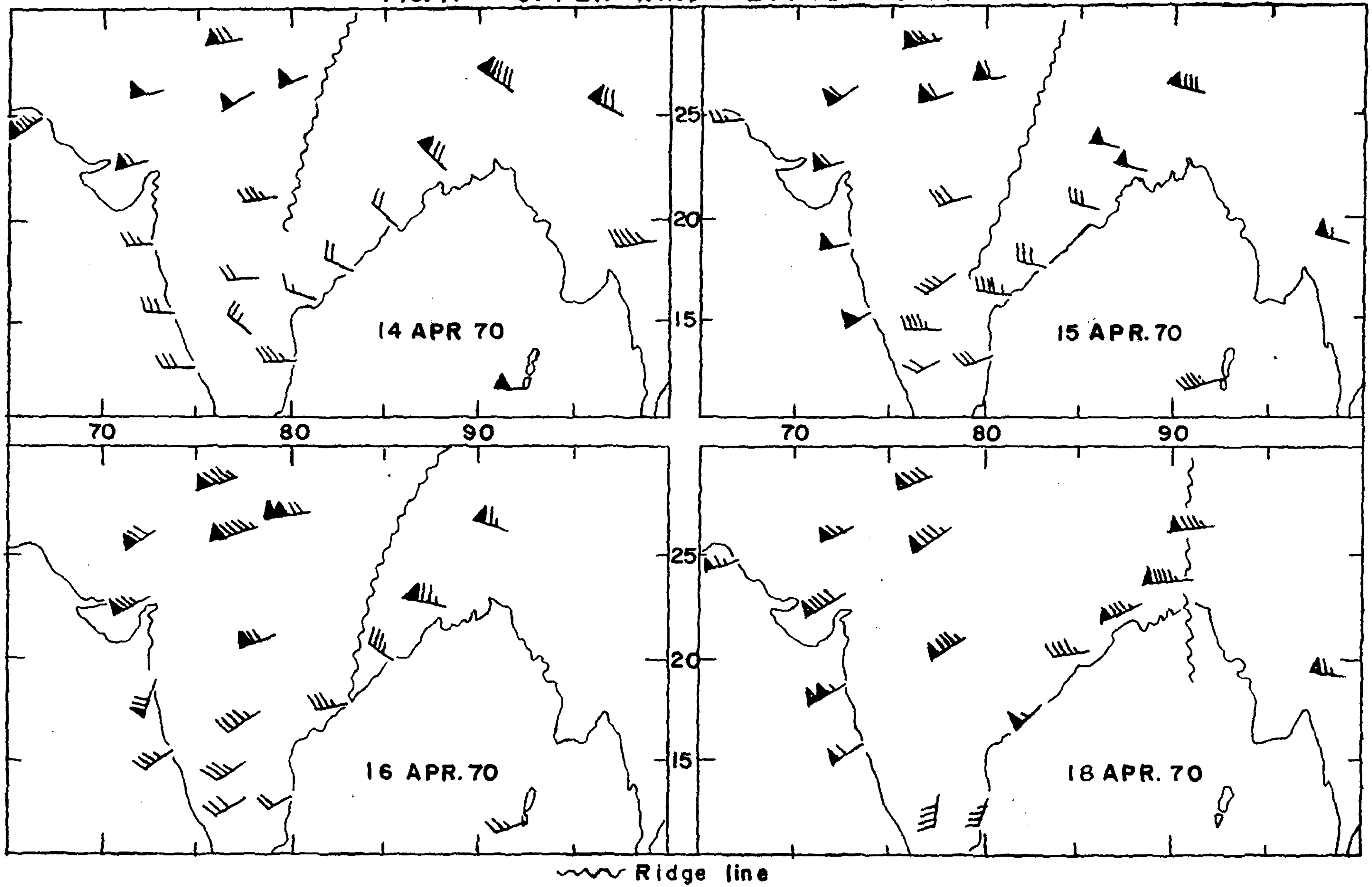


FIG. 17·5 VERTICAL TIME SECTION FOR GAUHATI : 15-19 APR.70

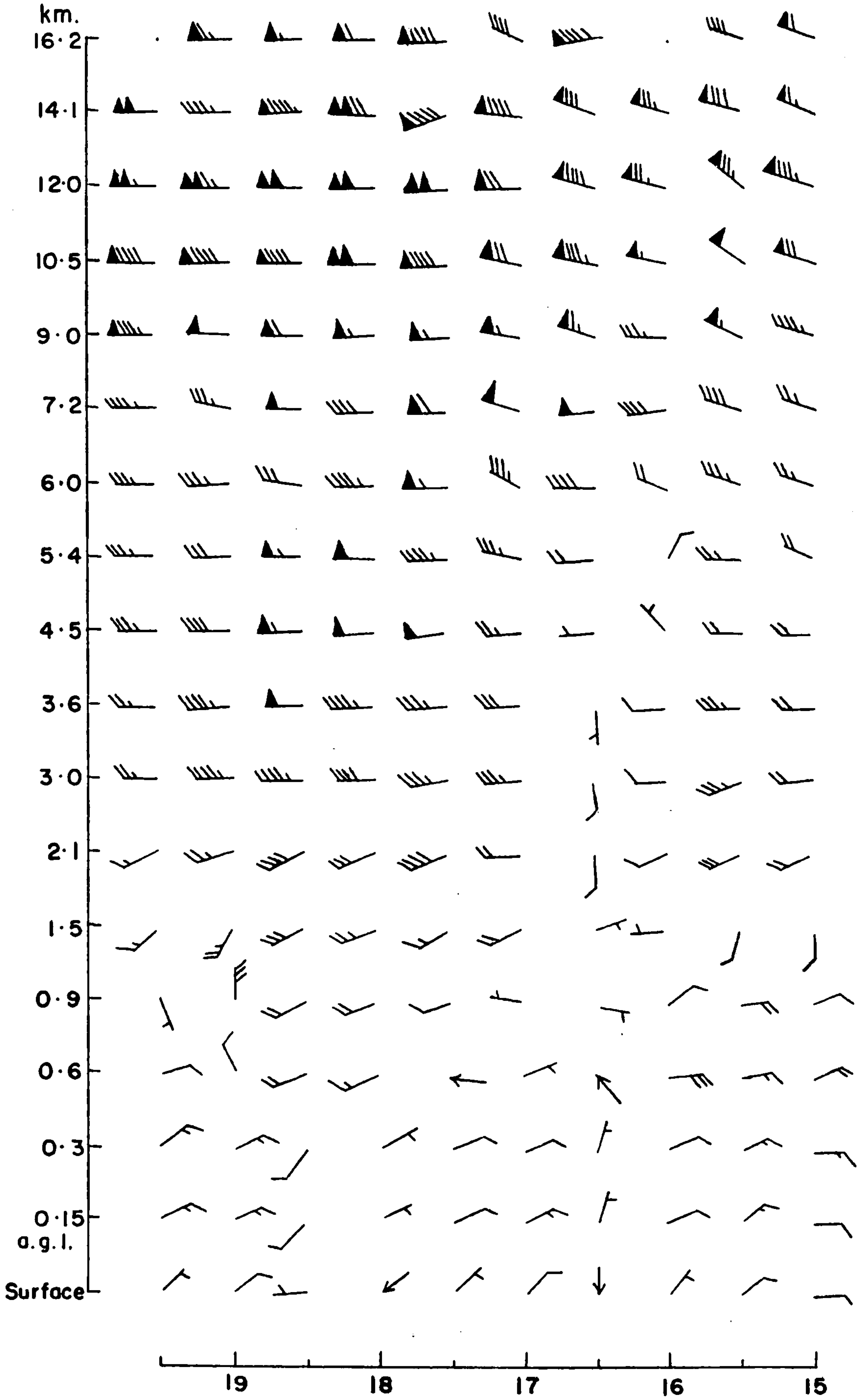


FIG. 18·1·1 SYNOPTIC CHARTS 0300 GMT 12 MAY 69

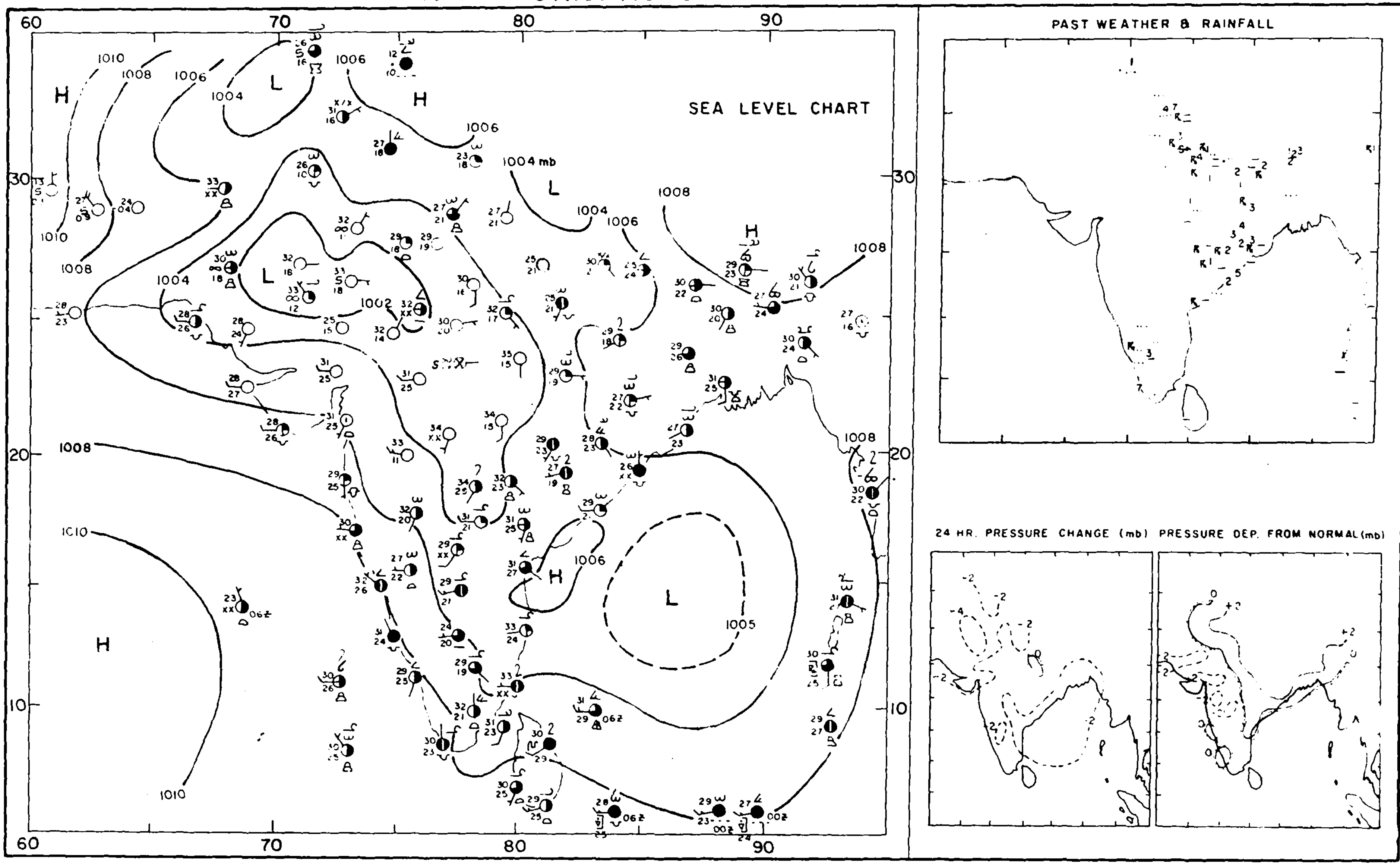
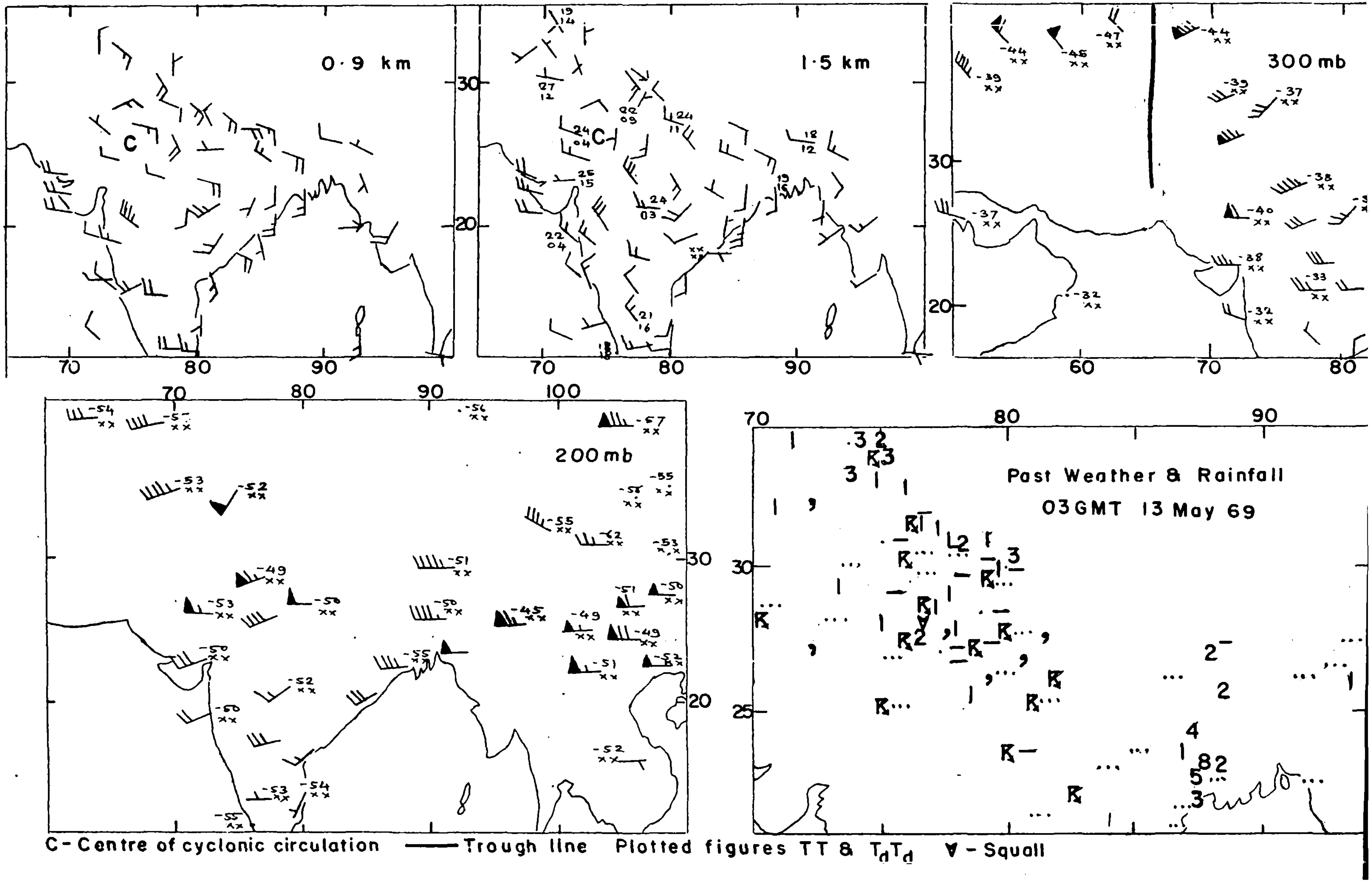
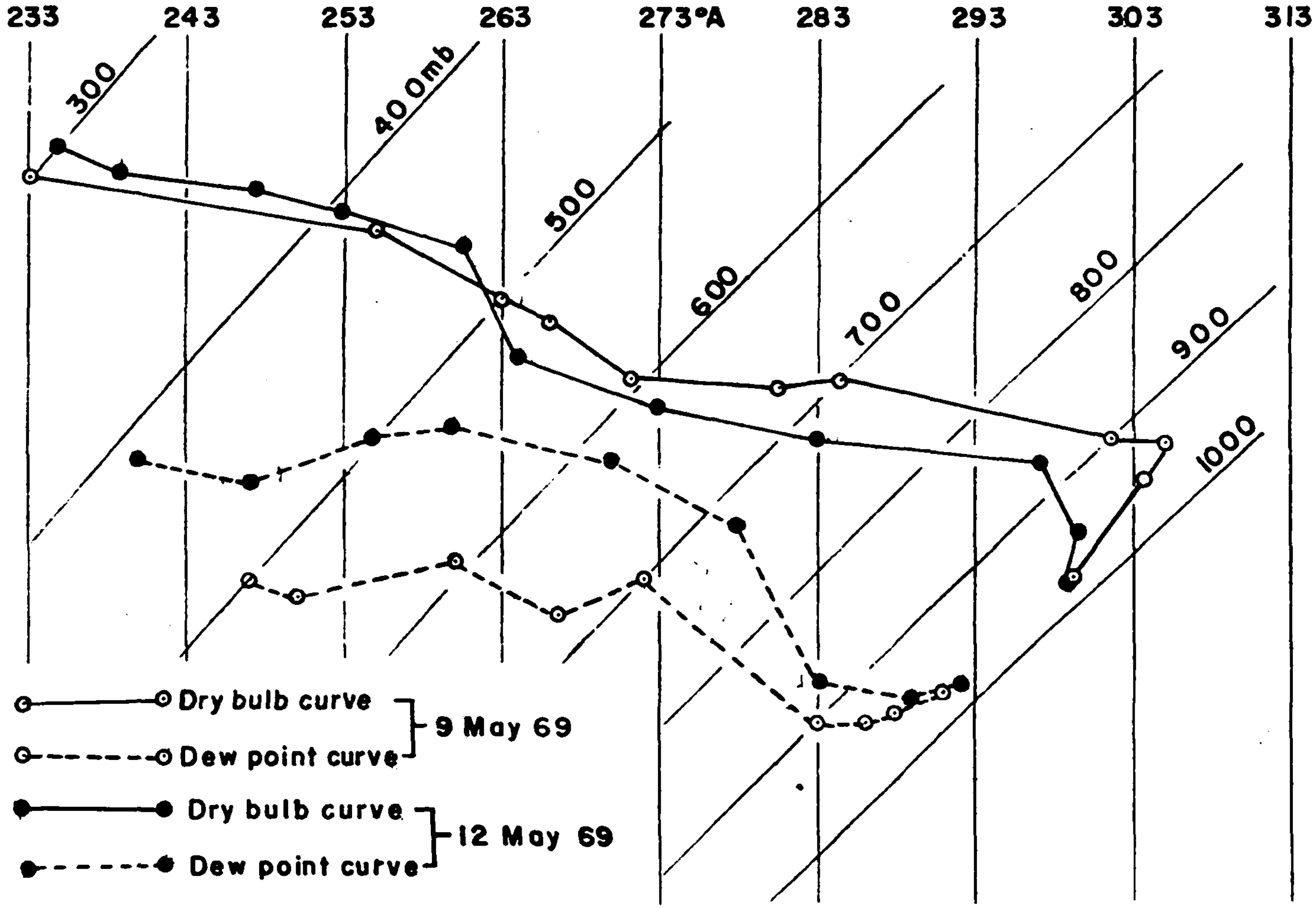


FIG. 18·1·2 UPPER WINDS 00 GMT 12 MAY 69



C - Centre of cyclonic circulation ——— Trough line Plotted figures TT & T_dT_d ∀ - Squall

FIG. 18·1·3 TEPHIGRAMS FOR NEW DELHI 00 GMT



9 May 69 :— Non Thunderstorm Day 12 May 69 :— Thunderstorm Day

FIG. 18·2·1 SYNOPTIC CHARTS 0300 GMT 9 APR. 72

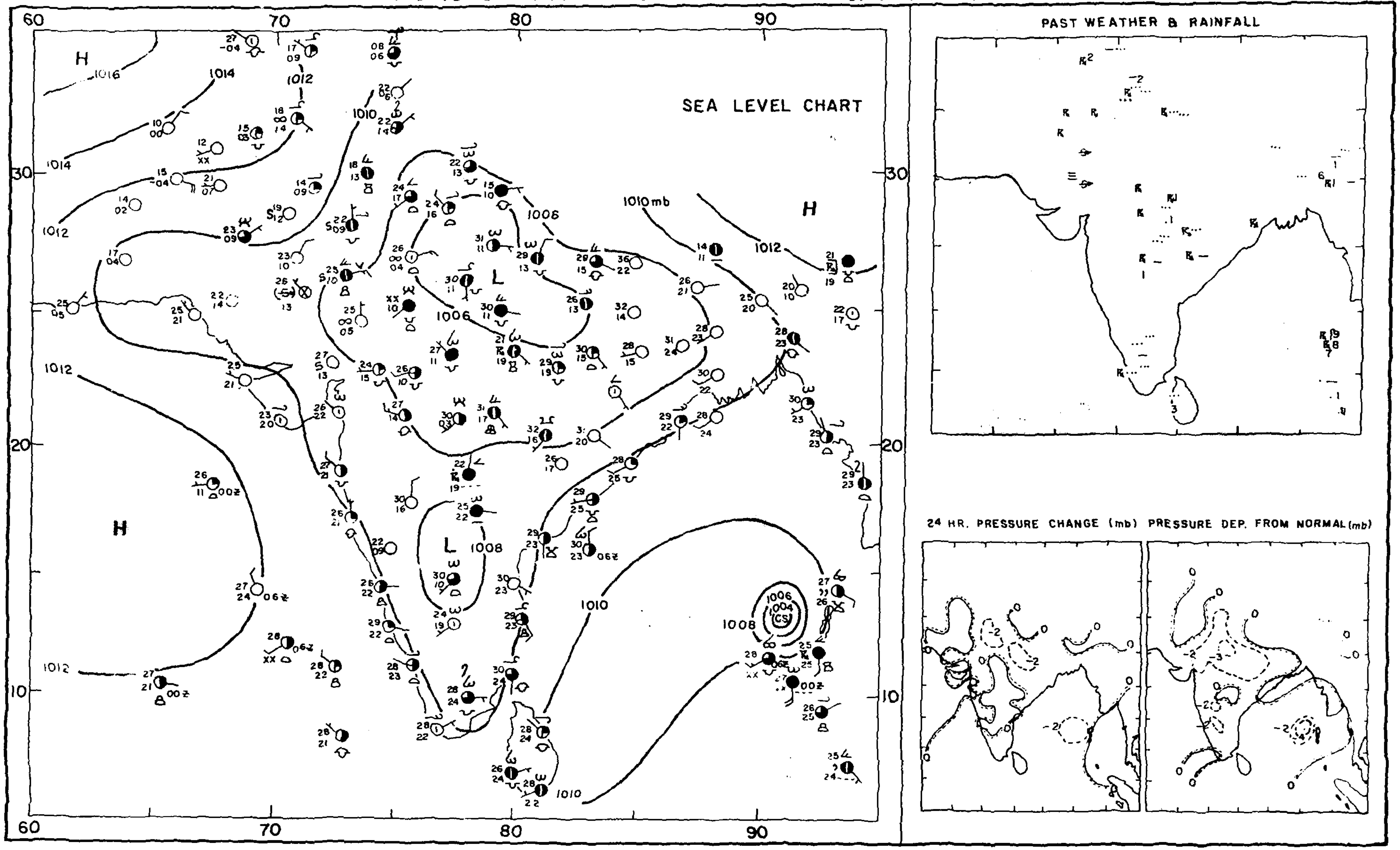
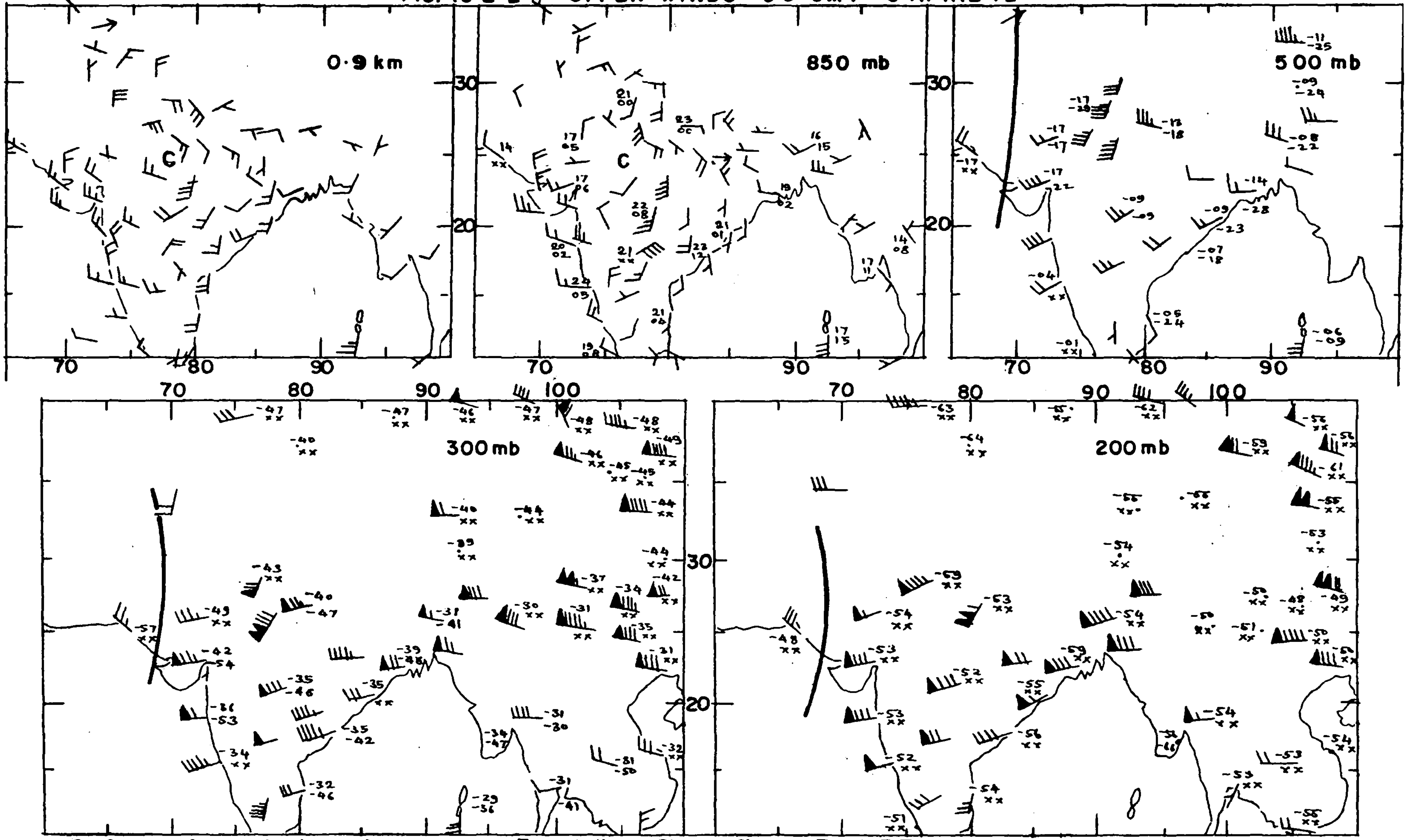


FIG. 18·2·2 // UPPER WINDS 00 GMT 9 APRIL 72



C - Centre of cyclonic circulation —— Trough line Plotted figures T T 8 $T_d T_d$

FIG. 18·2·3 PAST WEATHER AND RAINFALL

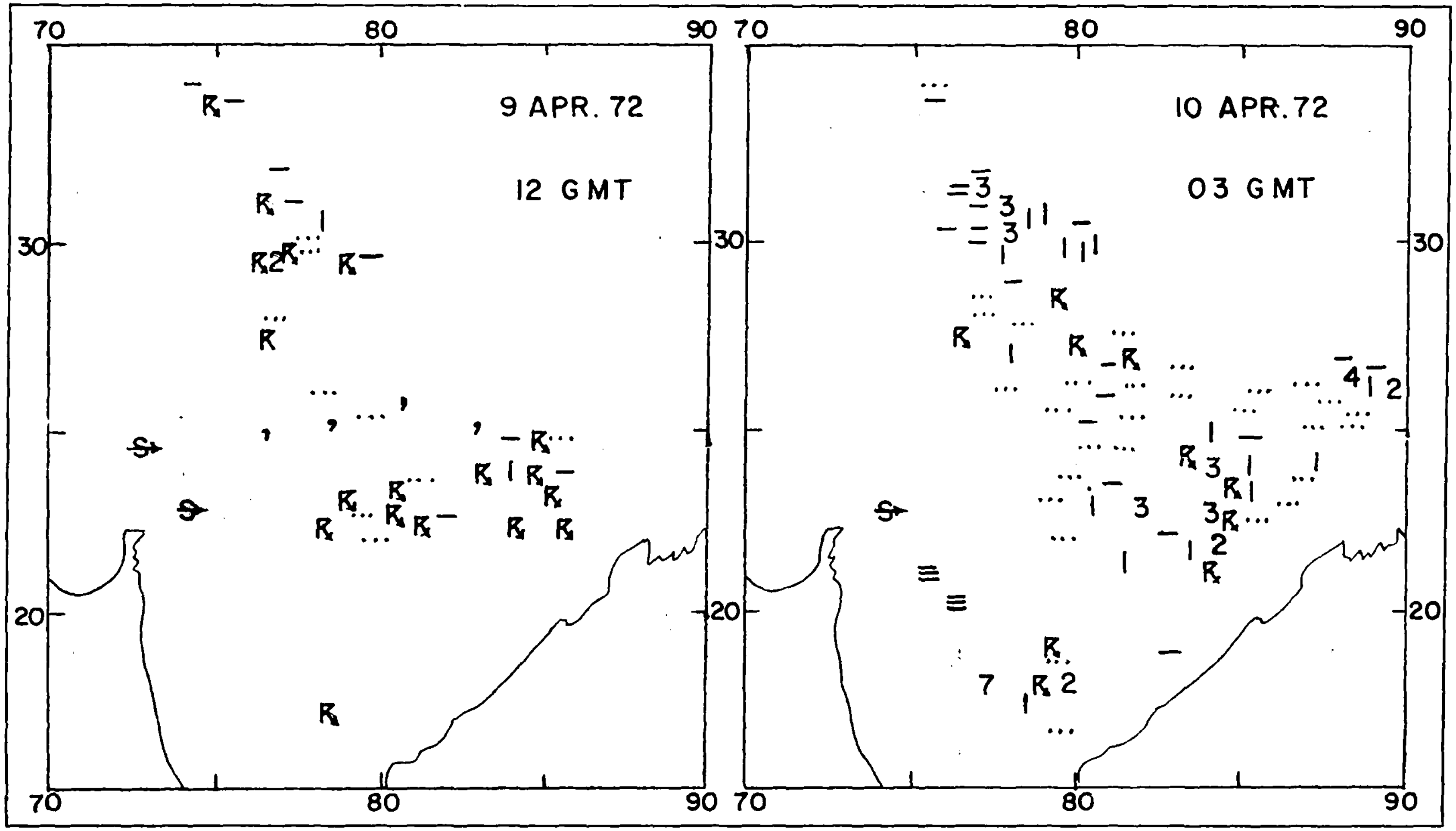


FIG. 18·2·4 NEW DELHI TEPHIGRAMS 00 GMT

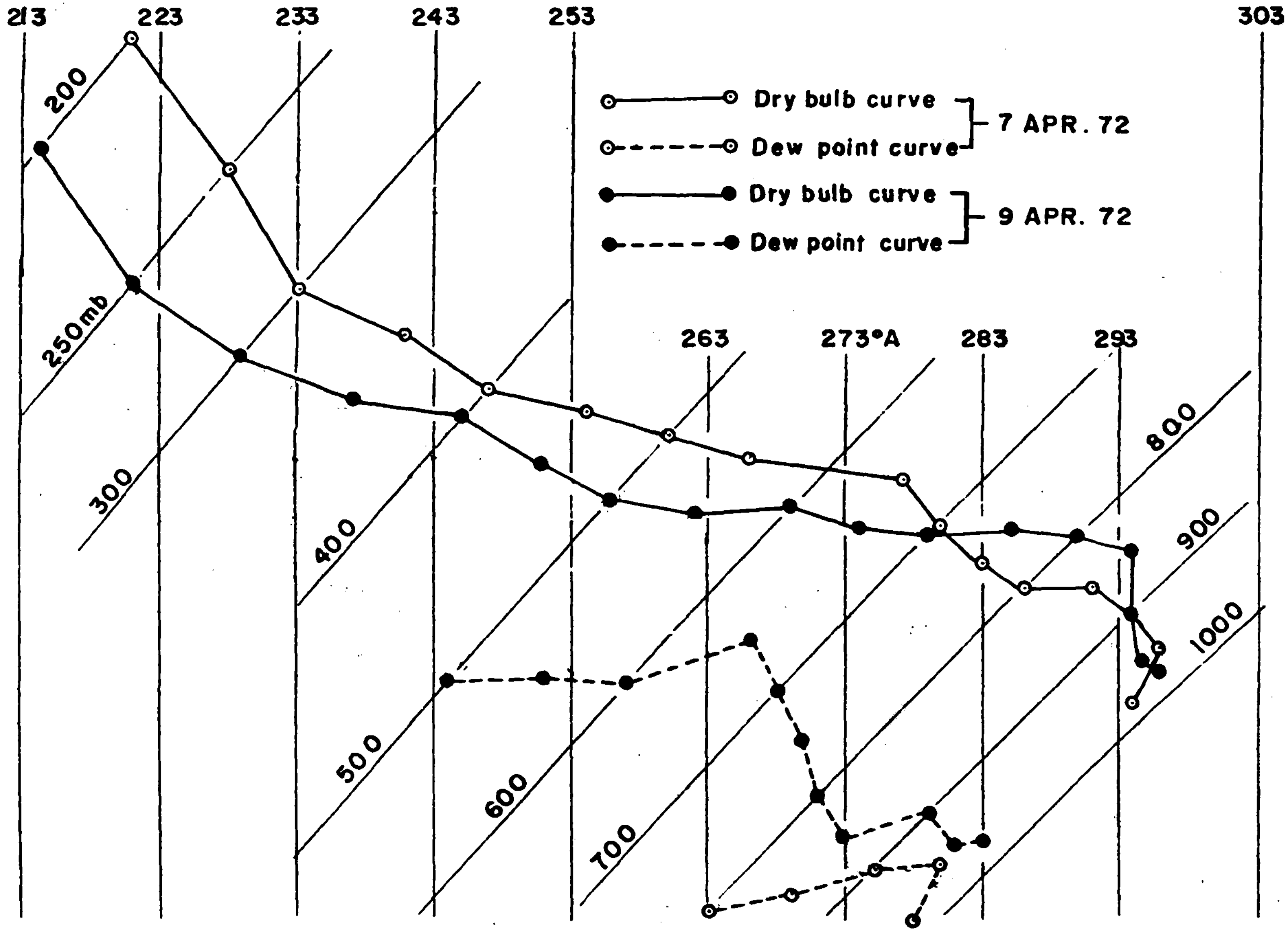


FIG. 19·1 **SYNOPTIC CHARTS** 0300 GMT 8 APR. 72

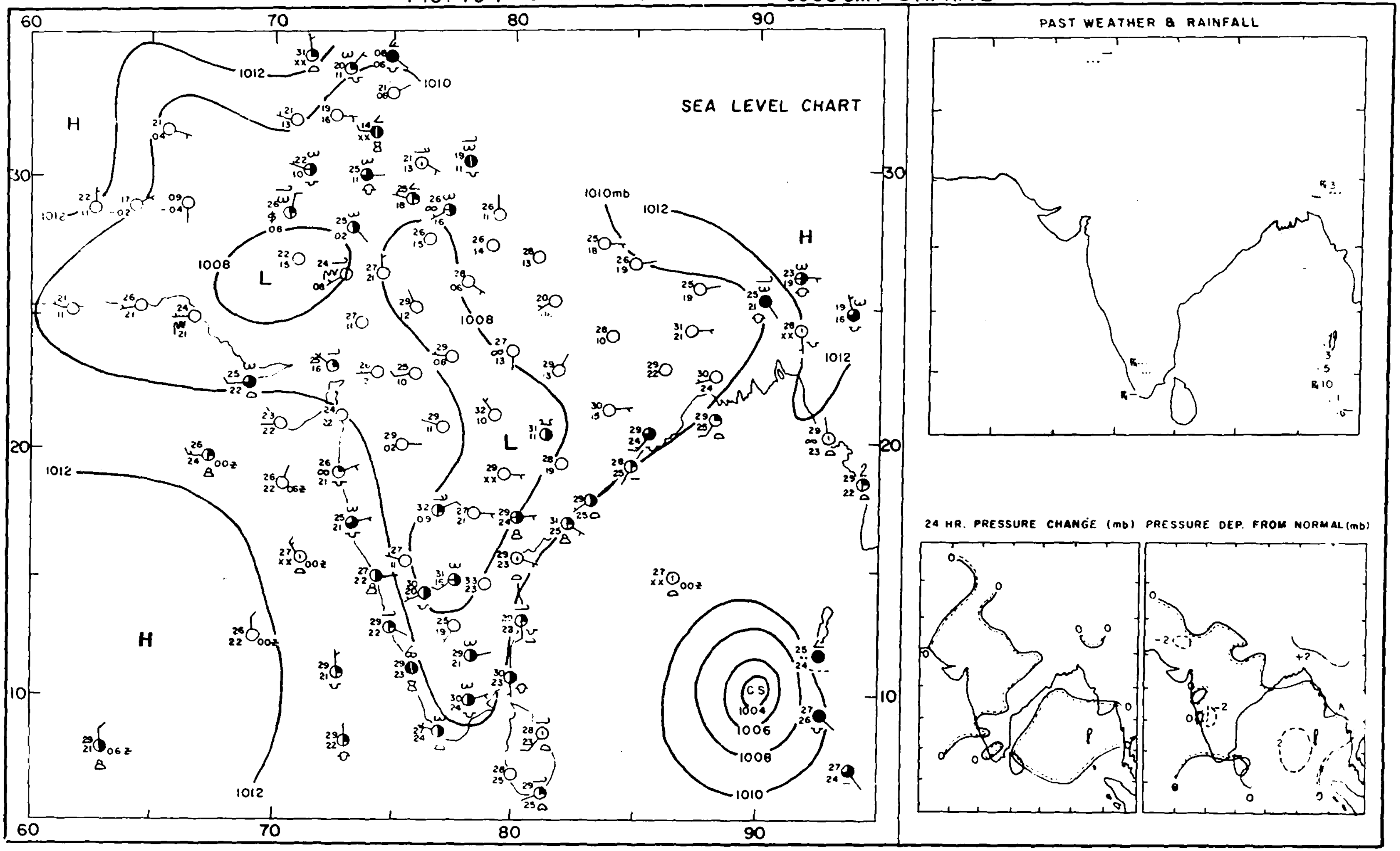
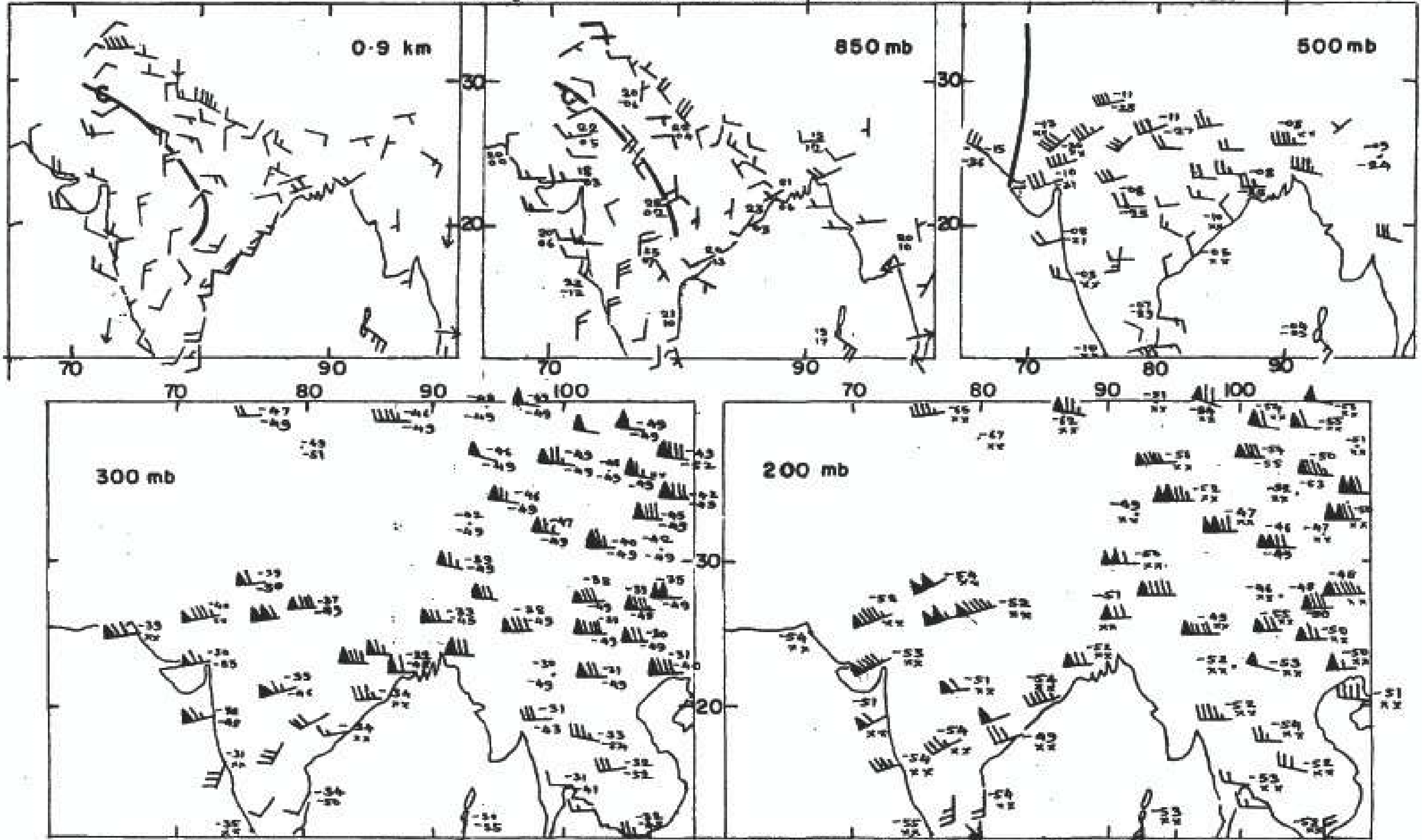


FIG. 19·2 UPPER WINDS 00 GMT 8 APR. 72



C - Centre of cyclonic circulation —— Trough line Plotted figures TT & T_dT_d

FIG. 19·3 SYNOPTIC CHARTS 0300 GMT 10 APR. 72

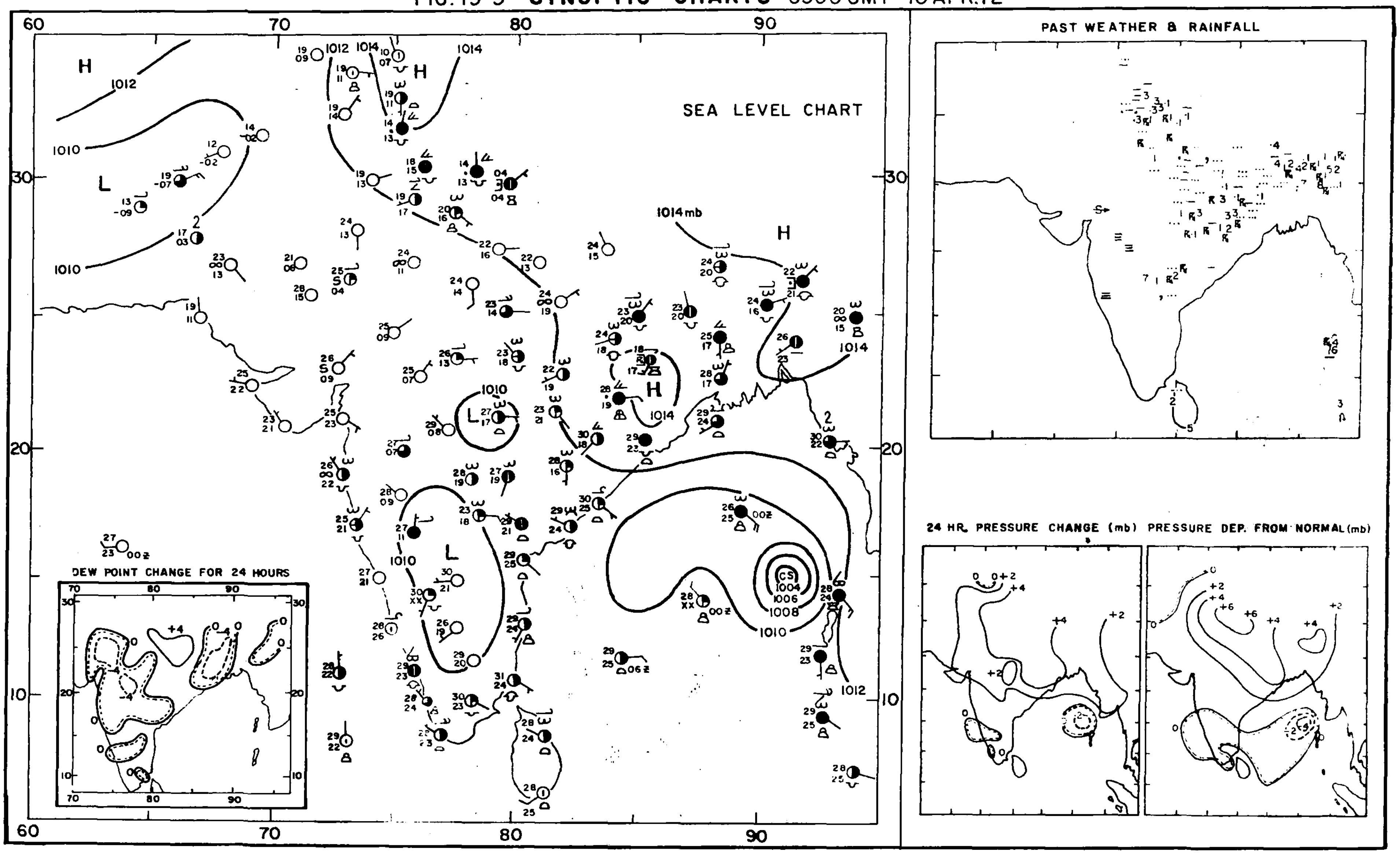
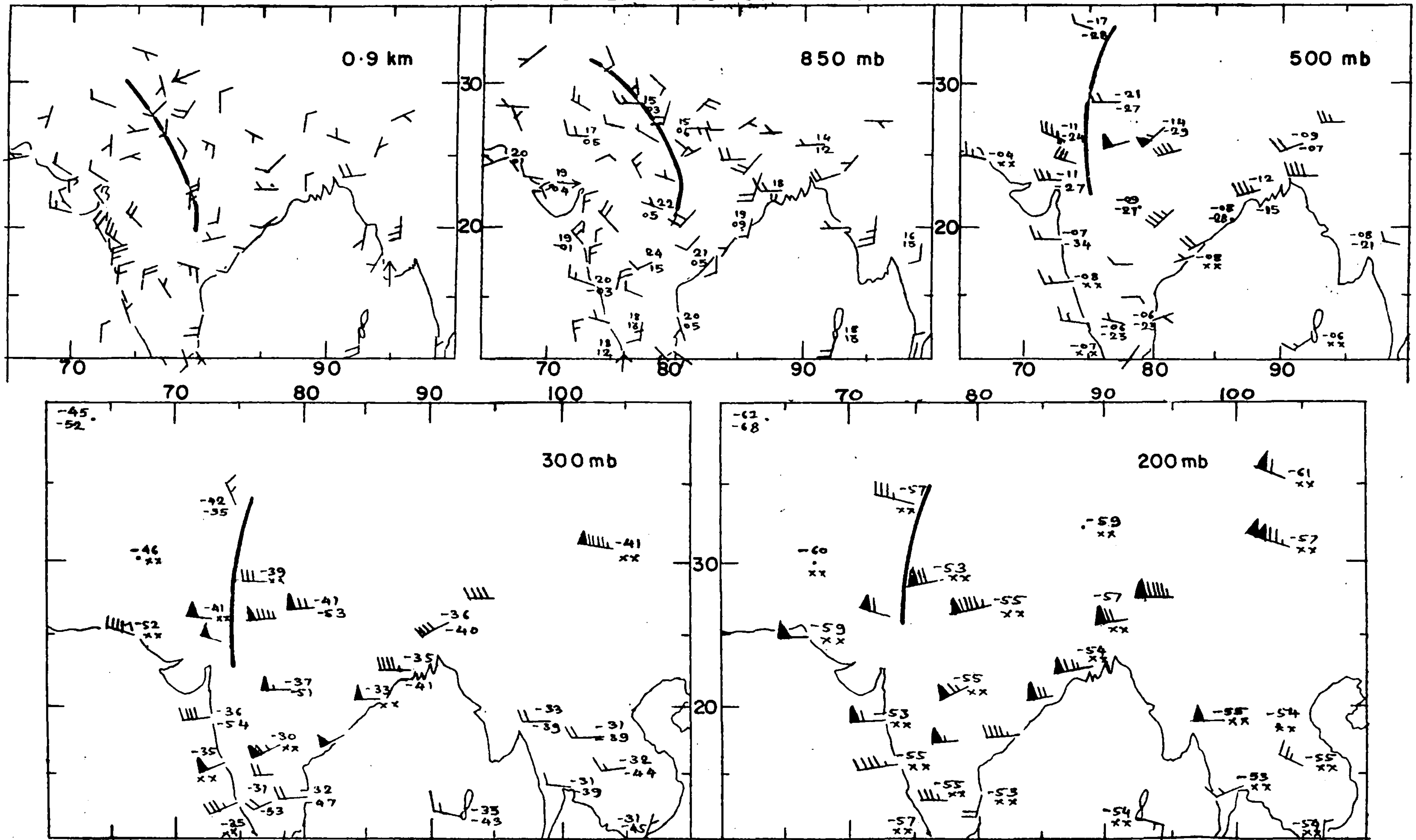
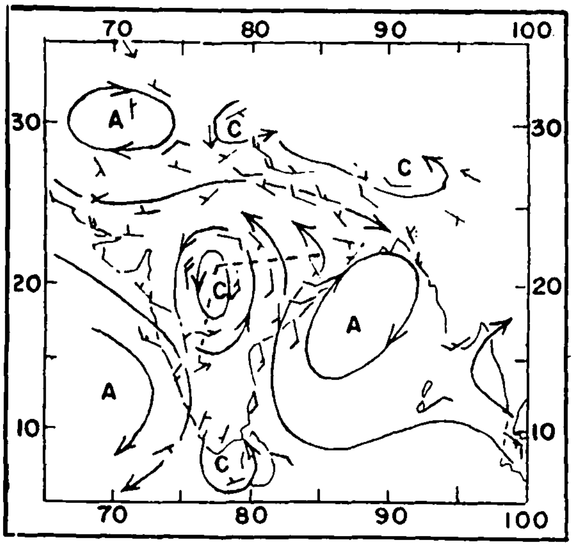


FIG. 19·4 UPPER WINDS 00GMT 10 APRIL 72



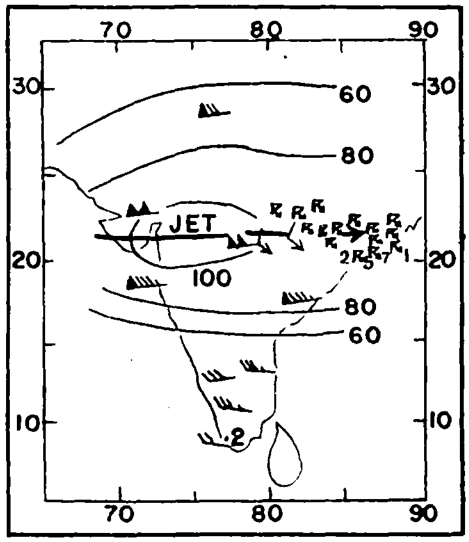
Trough line Plotted figures TT & T_dT_d

FIG. 19·5



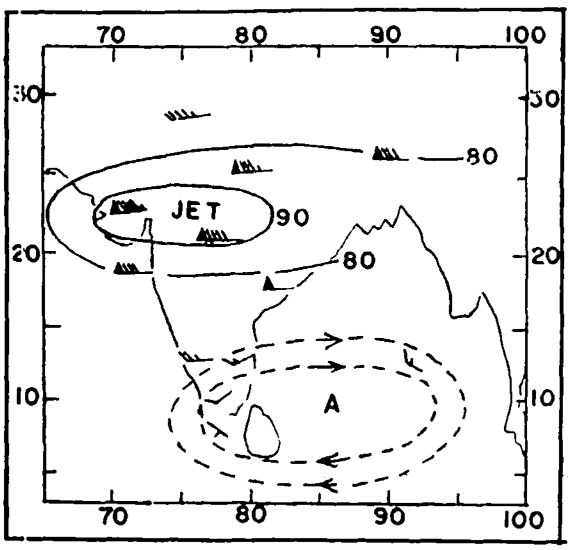
900 m asl winds and stream line flow pattern at 0000 GMT on 9 March 1962

----Trough line, ——Stream line
A – Anticyclonic, C – Cyclonic



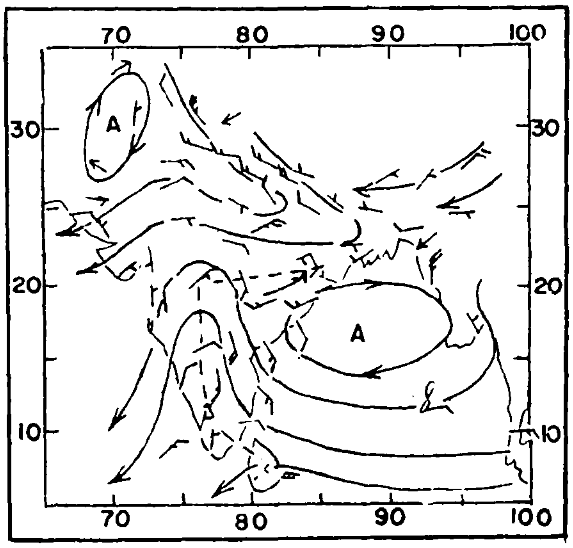
10.5 km asl winds at 0000 GMT on 9 March 1962

——Isotachs, wind speed in knots. Rainfall(cm) and weather symbols refer to 24-hour ending 0830 IST on 10 March 1962



9.0 km asl winds at 0000 GMT on 9 March 1962

—— Isotachs, wind speed in Kts
- - - Streamline, A–Anticyclonic



900 m asl winds and stream line flow pattern at 0000 GMT on 12 March 1962

---Trough line, ——Stream line
A – Anticyclonic

Reproduced from "Convective activity associated with Jet Stream" by D.R. Swaminathan, IJMG 1964, Vol.15 No.2, pp.247–250.(Figs.1–4)

FIG. 20·1 **SYNOPTIC CHARTS** 0300 GMT 15 APR. 71

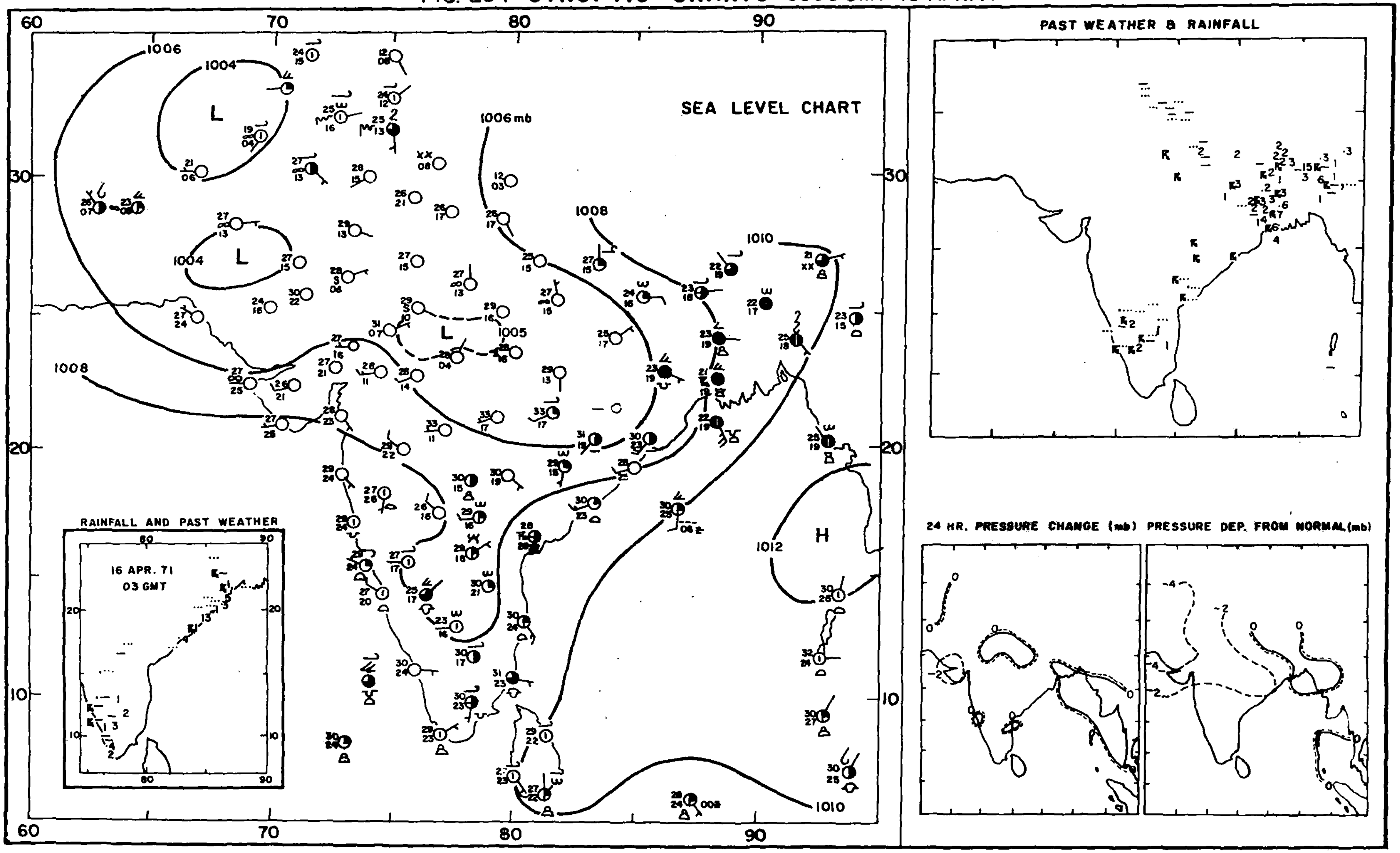
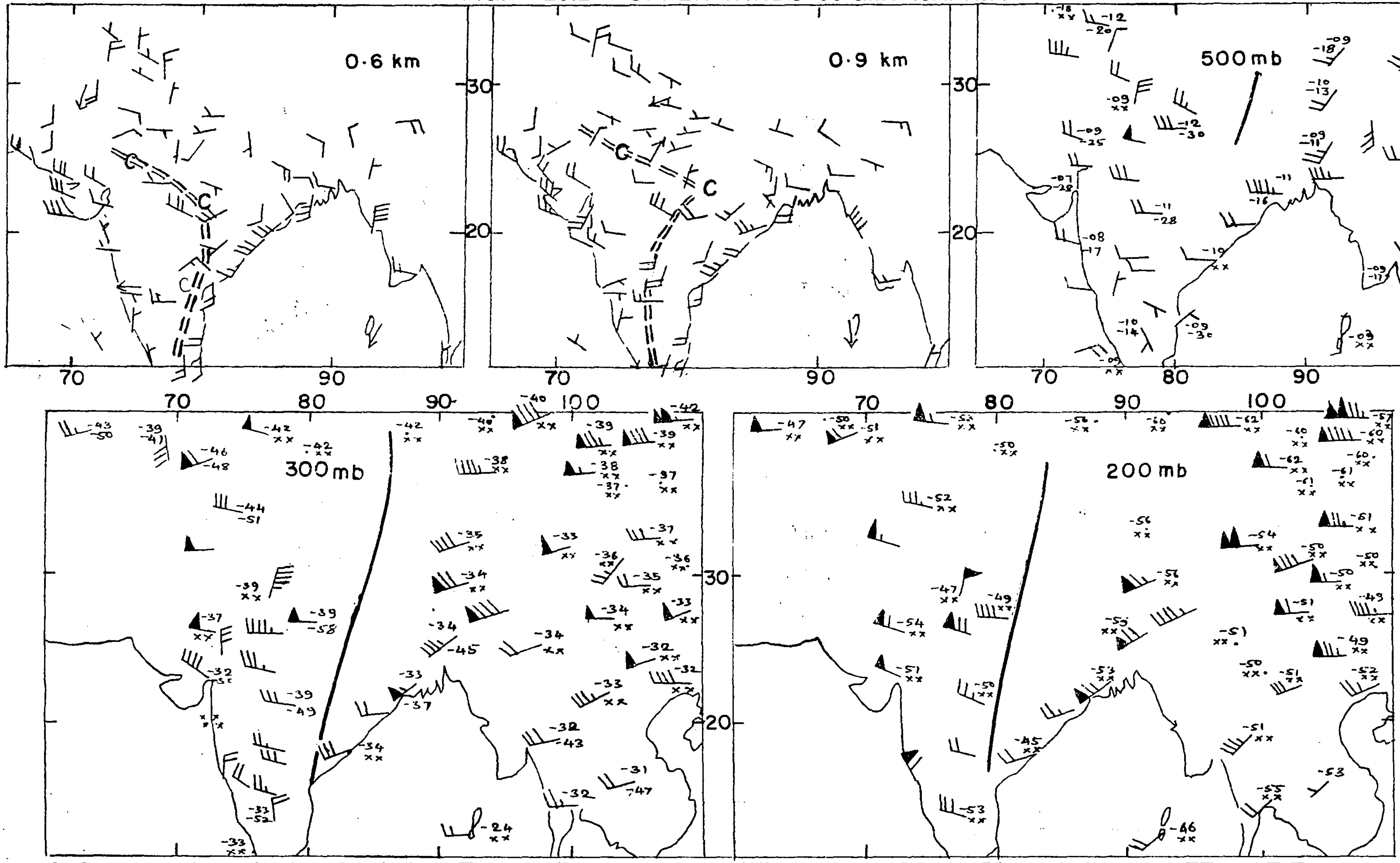
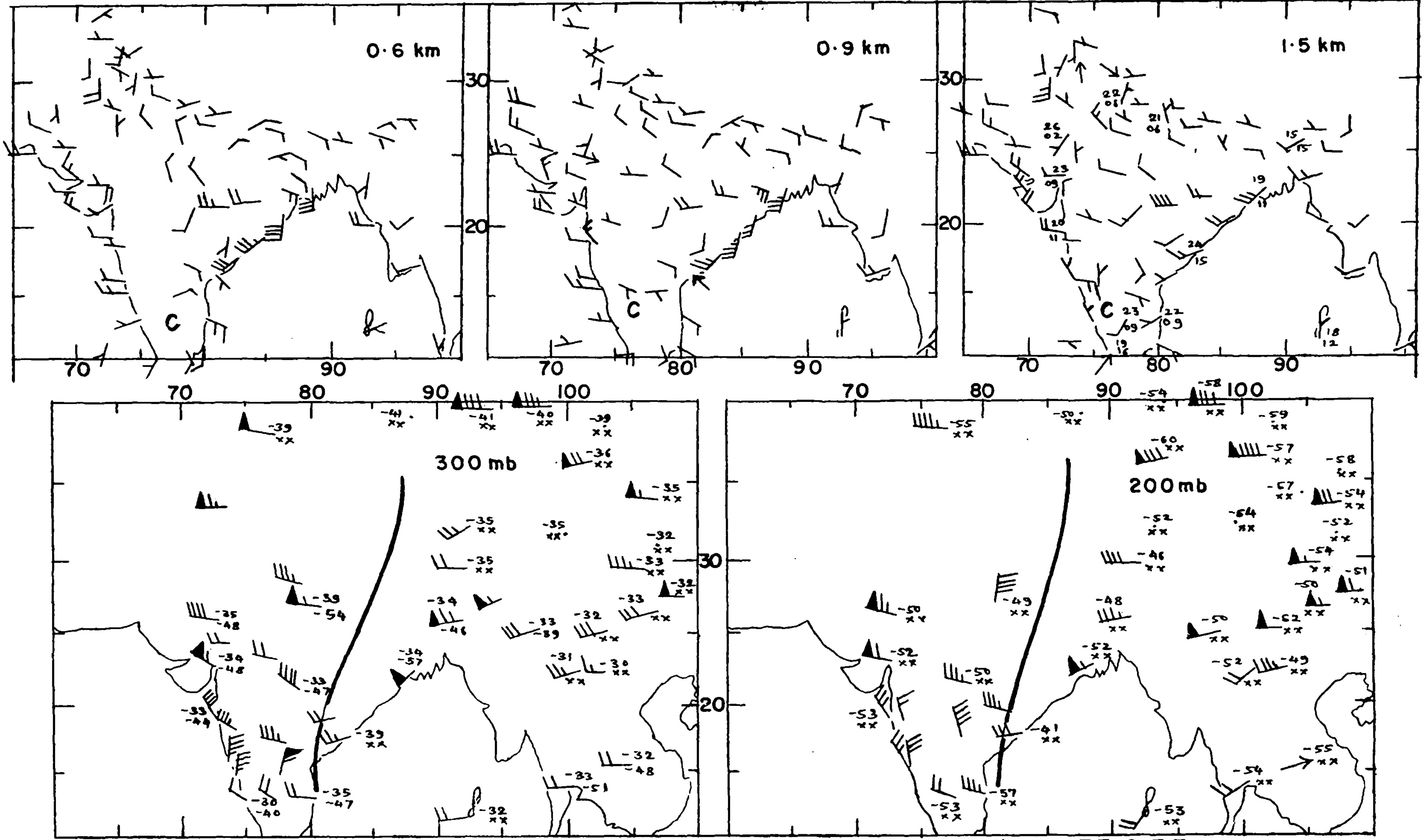


FIG. 20.2 UPPER WINDS 00 GMT 15APR.71



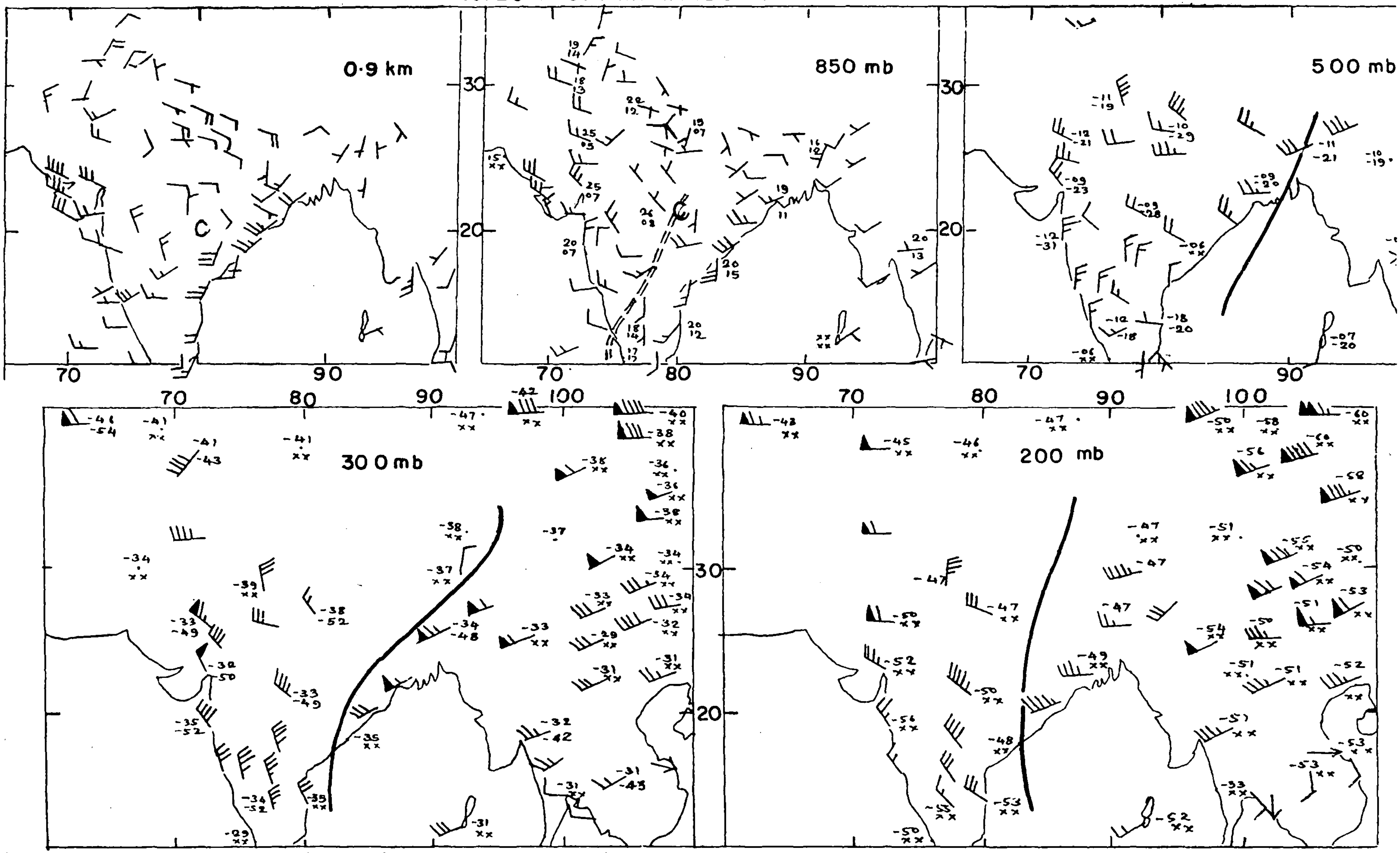
C-Centre of cyclonic circulation Trough line = = = = Wind discontinuity Plotted figures TT & T_dT_d

FIG.20·3 UPPER WINDS 12 GMT 15 APRIL 71



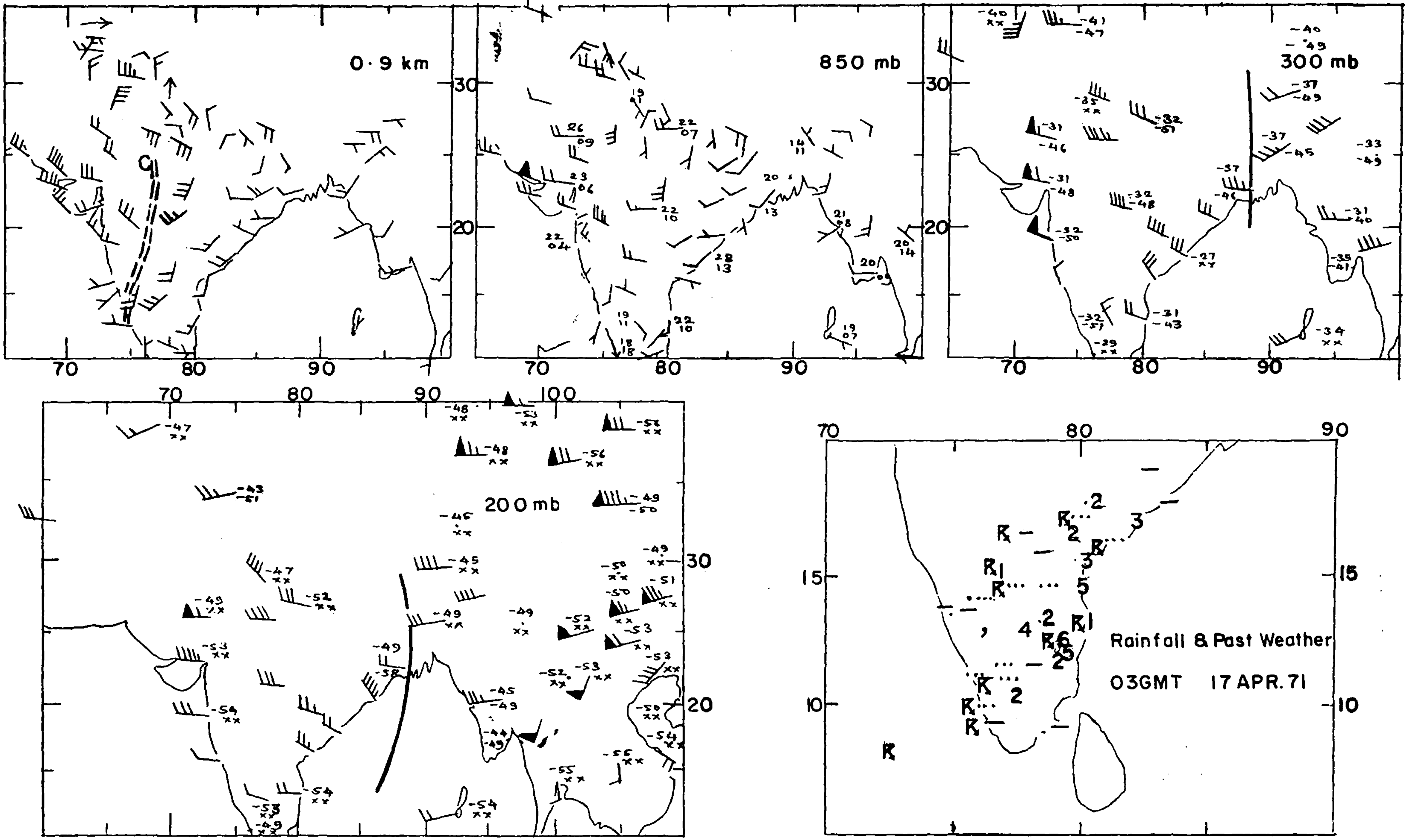
C - Centre of cyclonic circulation ——— Trough line Plotted figures TT & T_dT_d

FIG. 20·4 UPPER WINDS 00 GMT 16 APR. 71



C-Centre of cyclonic circulation —— Trough line ==== Wind discontinuity Plotted figures TT 8 T_dT_d

FIG. 20·5 UPPER WINDS 00GMT 17 APRIL 71



C-Centre of cyclonic circulation ——— Trough line ==== Wind discontinuity
Plotted figures TT & T_dT_d

FIG. 21·1 SYNOPTIC CHARTS 0300GMT 13 APR. 70

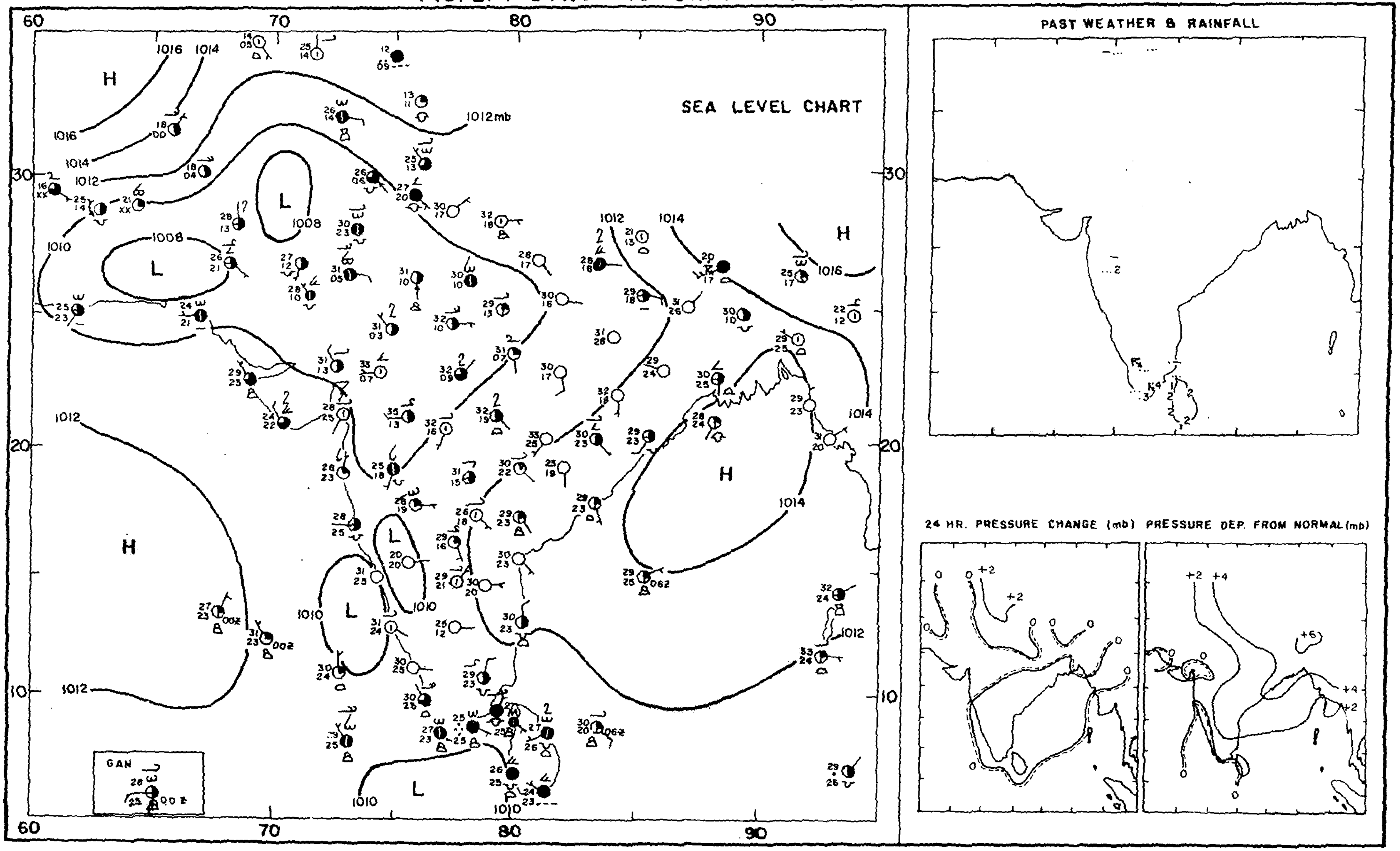
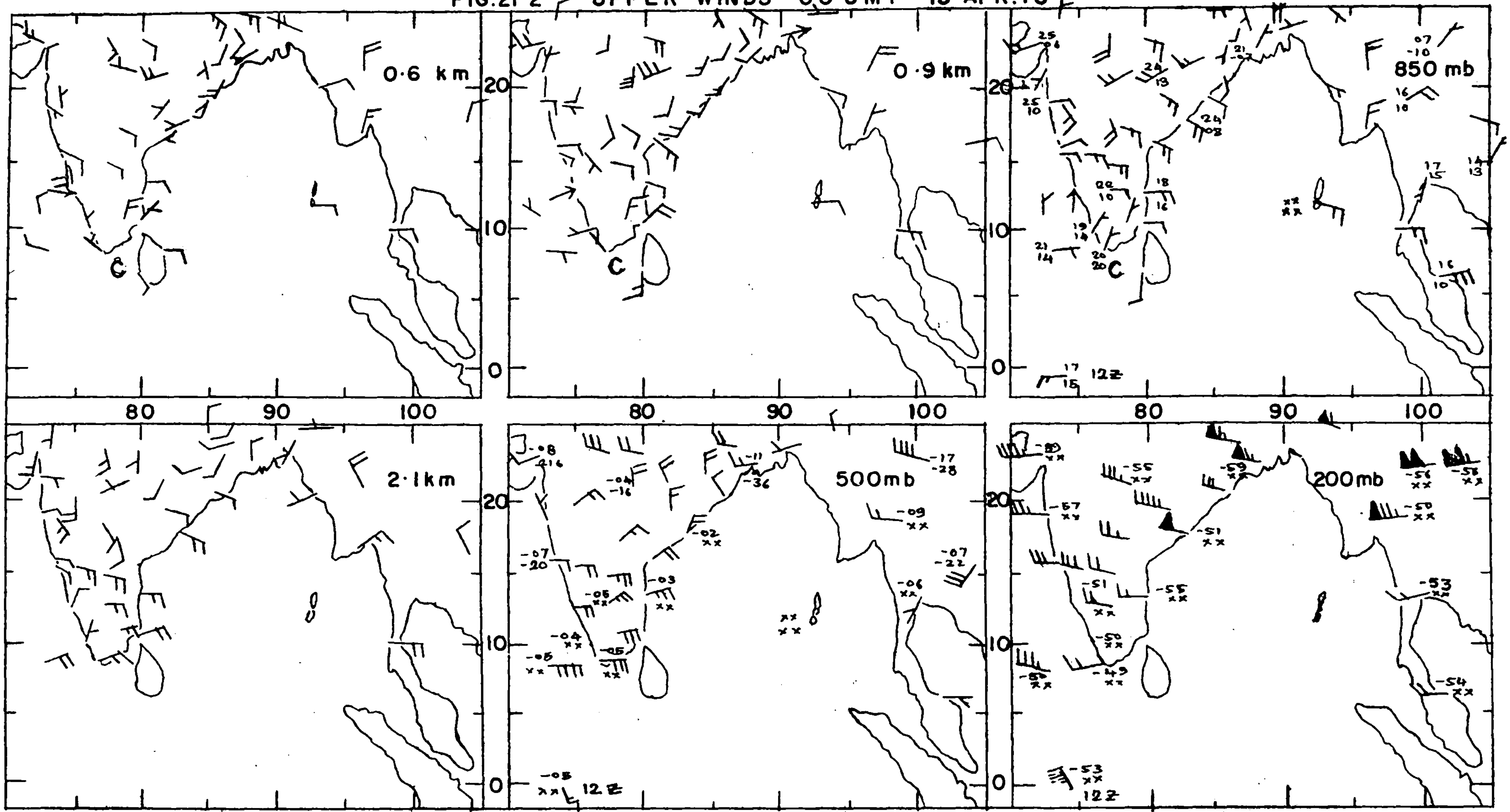


FIG.21·2 UPPER WINDS 00 GMT 13 APR.70



C-Centre of cyclonic circulation Plotted figures TT & $T_d T_d$

FIG. 21·3 SYNOPTIC CHARTS 0300 GMT 14 APR. 70

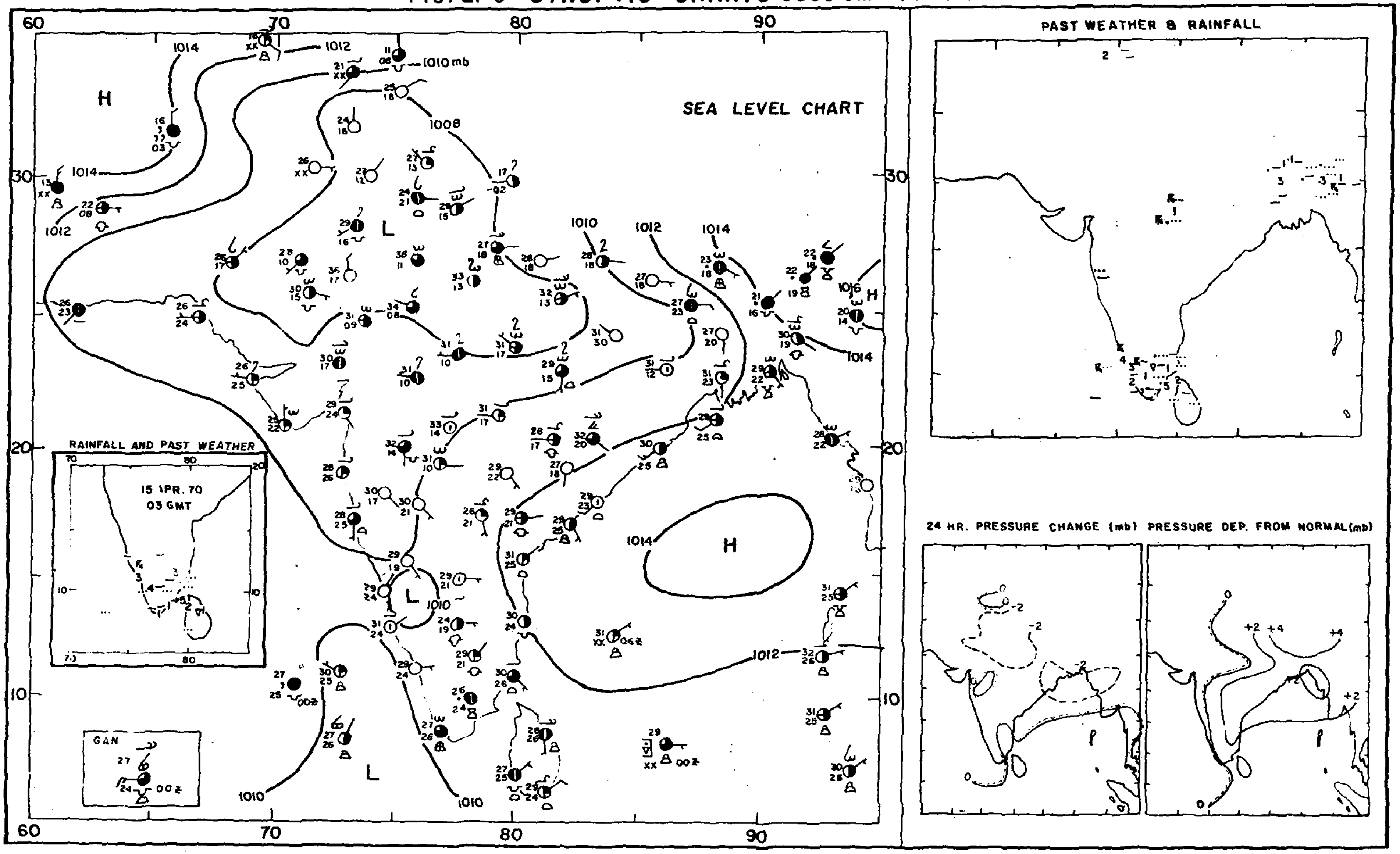
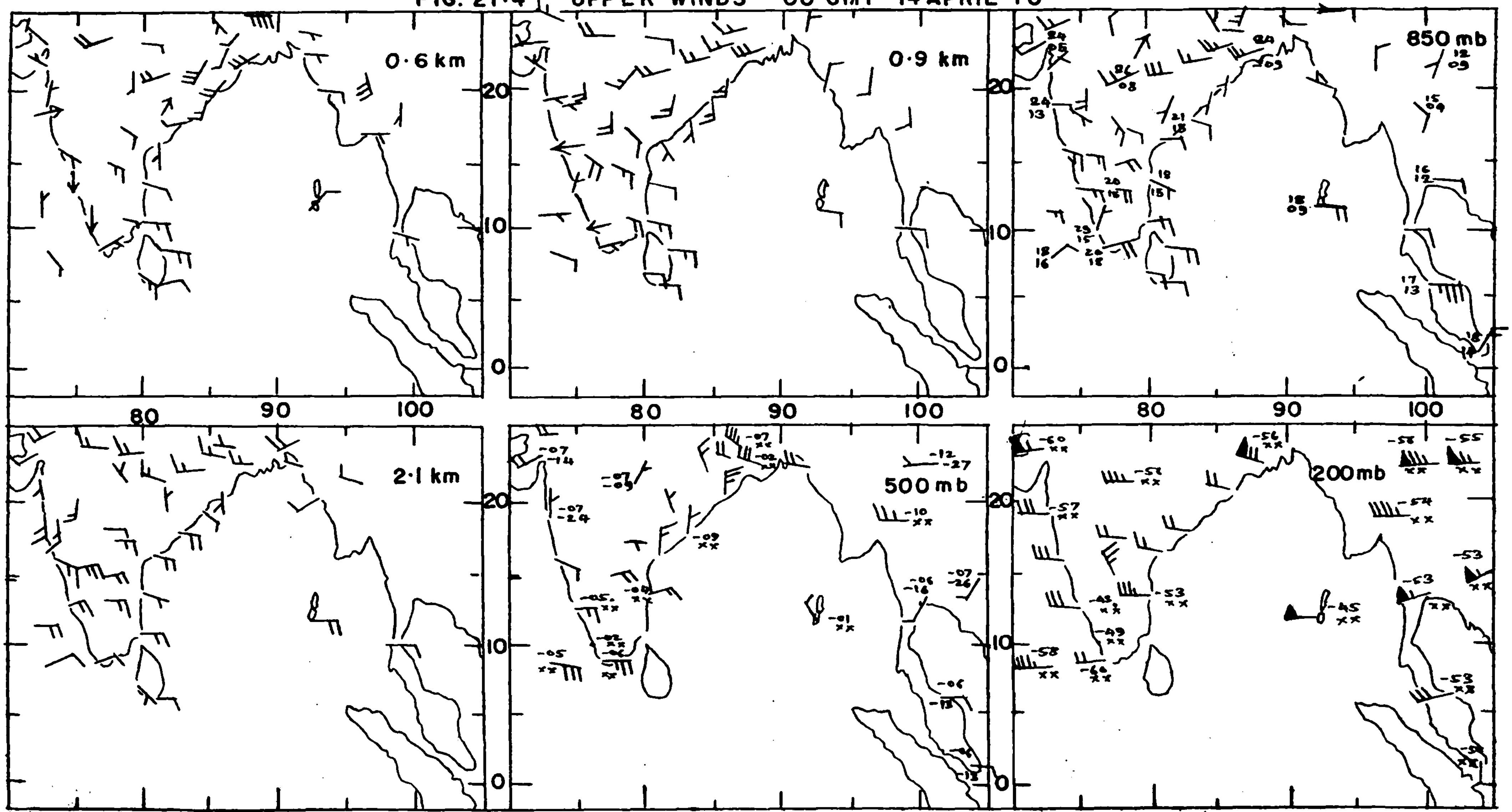
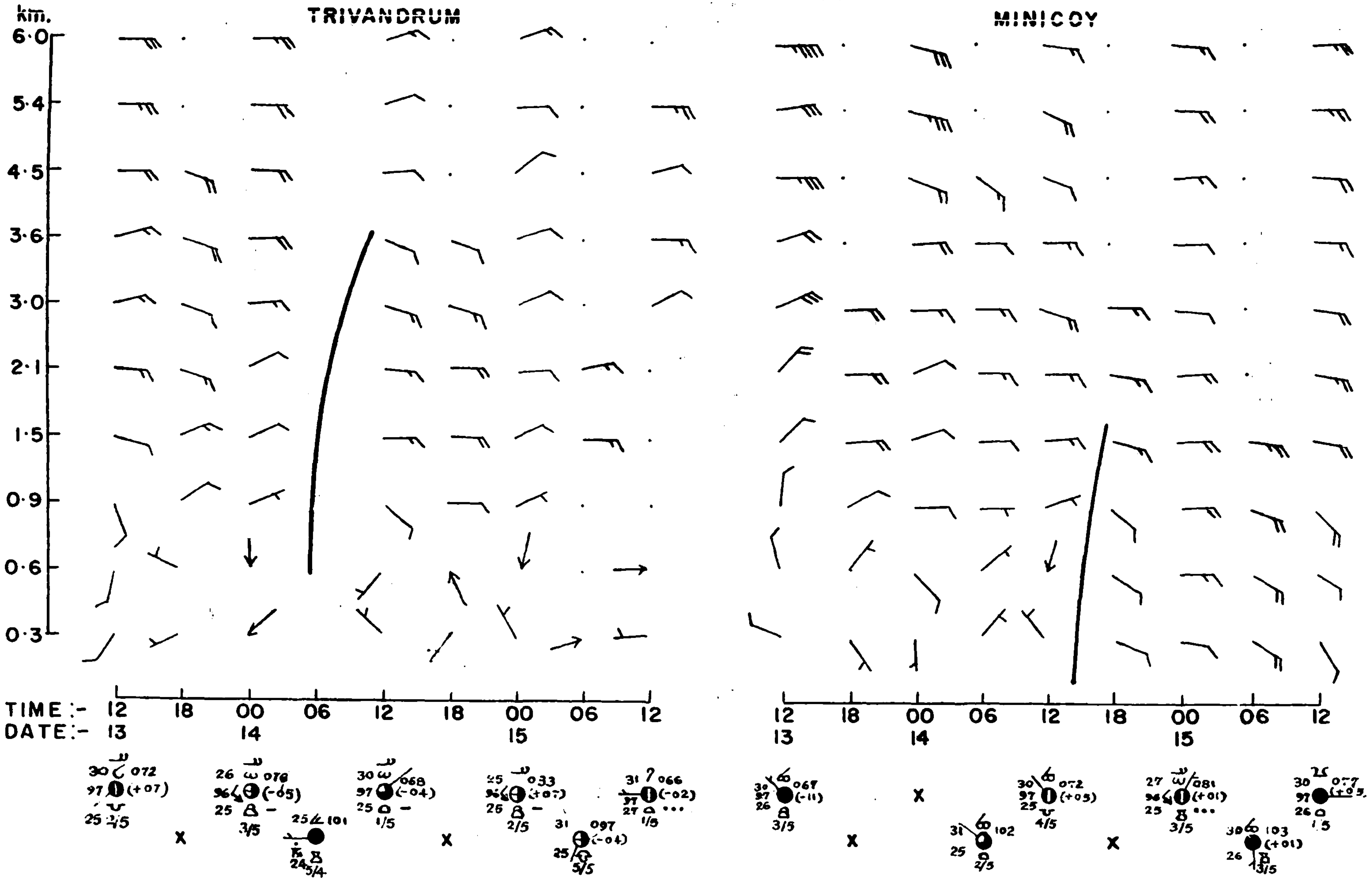


FIG. 21·4 UPPER WINDS 00 GMT 14 APRIL 70



Plotted figures TT & T_dT_d

FIG. 21·5 TIME SECTION CHART 13 – 15 APRIL 1970



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No. IV-16	Microseisms and Weather – A.N. Tandon and S.N.Bhattacharya.
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