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INDIA METEOROLOGICAL DEPARTMENT

# FORECASTING MANUAL

## PART III

DISCUSSION OF TYPICAL SYNOPTIC WEATHER SITUATIONS

### 4·1 WEATHER OVER THE INDIAN SEAS DURING THE POST-MONSOON SEASON

BY

V. SRINIVASAN AND K. RAMAMURTHY.

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# FORECASTING MANUAL

## Part III - Discussion of Typical Synoptic Weather Situations

### 4.1 Weather over the Indian Seas during the Post-Monsoon Season

by

V. Srinivasan and K. Ramamurthy

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## 1. Introduction

1.1 The Weather over the Indian Peninsula during the Post-Monsoon months of October to December has been described in the article on "Northeast Monsoon" (FMU Report No. IV-18.4). In the present report we wish to consider the weather over the Indian Sea areas during the post-monsoon season. There are a few aspects common to both the reports and the two reports may, therefore, be considered as complementing one another.

1.2 The common synoptic situations over the Indian sea areas during the post-monsoon season are:-

i) depressions and cyclonic storms,

ii) low pressure areas moving from east to west and

iii) well-marked seasonal trough

1.3 We will begin with a discussion of depressions and cyclonic storms. Very extensive literature is now available on tropical storms covering both the observational and theoretical aspects. It is obviously not possible to condense all of them in a small report like the present one. Consequently, a summary of our present knowledge on tropical storms, with emphasis on only such aspects of cyclones, which are necessary for synoptic analysis of charts, and prognosis of future weather, has been included in this report. This has been done mainly with reference to conditions over the Indian sea areas and is concerned with forecasting aspects. This will be followed by a brief discussion on the other types of synoptic systems, i.e., low pressure areas and seasonal trough. The report concludes with a discussion of some typical storms over the Indian seas.

## 2. Classification of Tropical Disturbances

2.1 Tropical disturbances that occur over the sea areas cover a wide range of intensities - from a low pressure area with winds of strength 10/15 knots to a severe cyclonic storm where the maximum wind strength may exceed 100 knots. The terminology and definitions used by the India Meteorological

Department to classify the tropical disturbances in the Indian sea areas are given below. These have been used by the Department from 1.10.1954:

TABLE – I

| Low Pressure System | Wind speed in the circulation (Knots) |
|---|---|
| Low pressure area | $<$ 17 |
| Depression | 17–27 |
| Deep depression | 28–33 |
| Cyclonic storm | 34–47 |
| Severe cyclonic storm | $\geq$ 48 |

(Relevant extracts from the Recommendations of the Forecasting Officers' Conferences 1951, 1960 and 1972 on this subject are given in Appendix I, Extracts from Forecasting Circular No.1 of 1972 are also given in this Appendix)

2.2 It should be noted that the primary meteorological element on which these definitions are based is the maximum wind in the circulation. The wind may be either an actual report or an inferred one. Though a table (Appendix I) has been drawn up relating pressure gradients and pressure departures to the wind strength, the pressure is only an additional aid to infer wind speeds.

2.3 In the isobaric field, a low pressure area is delineated by a single closed isobar drawn at 2 mb interval. Sometimes, it may be only an odd-valued isobar. The circulation may be sometimes better developed in the upper air than at the surface. In the case of a depression, there are at least two closed isobars at 2 mb interval.

2.4 Where the maximum wind in the circulation reaches 64 knots or more (i.e. B.F.12, Hurricane Force), the system is described as "a severe cyclonic storm with a core of hurricane winds". The classification of tropical disturbances adopted by the India Meteorological Department is in agreement with WMO classification.

2.5 The term 'Typhoon' is used to describe disturbances in West Pacific when the maximum winds exceed hurricane force, while the term 'Hurricane' is used to describe similar disturbances in the Atlantic and East Pacific. Recently,another term "Super Typhoon" has been brought into use in the West Pacific to include the stronger and larger typhoons where the sustained winds attain a speed of at least 130 knots. (This is almost twice the intensity of a typhoon (i.e.) about twice 64 knots). There are also other special names used in the other parts of the world to define an intense tropical storm.

## 3. Life Cycle of a Cyclonic Storm

3.1 The life cycle of a severe storm may be divided into the following stages:

i) Formative stage*: The formative stage covers the period from the genesis of the cyclonic circulation as a low pressure area, through the stage of a depression till it reaches the intensity of a severe cyclonic storm. At the end of this stage, the "eye" and the "wall cloud" are formed. According to Malkus, winds cannot reach speeds greater than about 45 mph ( $\approx$ 40 knots) until an 'eye' is formed. The pressure fall is very slow during the formative stage, and the central pressure reaches 10 mb or so below the normal. In the Indian sea area, the normal pressure in the seasonal trough during the post-monsoon period is about 1010 mb; consequently, the central pressure in the formative stage of a cyclone is about 1000 mb.

ii) Immature stage: During this stage, the central pressure rapidly falls and winds strengthen. The bands of clouds and rain get organised. The area of very strong winds is still small. The central pressure and the winds reach their maximum limits.

iii) Mature stage: The main feature of this stage is that the entire circulation expands outwards while pressure remains relatively constant at the centre. The area covered by winds of hurricane force increases, and the area of strong

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* The description of 'Formative' and 'Immature' stages given here corresponds to what is described in U.S. Weather Bureau, Forecasting Guide No. 3 – "Hurricane Forecasting". This description varies from author to author.

winds extends further from the centre.

iv) Decaying stage: This is the stage when the system weakens. The weakening may take place on account of the cyclonic storm entering land, or moving into regions of cold waters. While those that move inland or over cold waters may weaken rapidly, those that recurve in our latitudes and get into the westerlies retain their structure and the weather associated with them continues to be severe, unlike in some other parts of the world.

3.2 The formative stage is usually a slow process; it may be spread over several days – by even as much as a week. The immature stage, when the cyclonic storm rapidly deepens, is a relatively quick process. It may occur within 24 hrs. Sometimes, the intensification is very rapid and the system may develop from a deep depression to a severe cyclonic storm in a few hours time as in the case of November 1960 storm which crossed the coast near Madras. In the formative stage the strong winds in the cyclonic storm are also confined to a very small area; consequently, storm in the formative stage may even pass through the conventional data network without being noticed. The mature stage, which marks the outward expansion of the cyclonic circulation may again last for several days. The dissipating stage may also be rapid. As Arabian Sea and Bay of Bengal are of limited extent (unlike the Atlantic or the Pacific), storms in Indian sea areas may often cross coast and weaken before they develop fully and reach the mature stage.

3.3 An analysis of the time intervals between the successive stages of development (depression, cyclonic storm and severe cyclonic storm) is given in Table II.

TABLE - II

(a) Percentage frequency of depressions intensifying into cyclonic storms (in Bay of Bengal and Arabian Sea) during different time intervals

(Period of data - 1891 to 1970)

| | 0-12 hrs. | 12-24 hrs. | 24-36 hrs. | 36-48 hrs. | 48-72 hrs. | 72-96 hrs. | 96-120 hrs. |
|---|---|---|---|---|---|---|---|
| October | 14 | 30 | 14 | 25 | 5 | 7 | 5 |
| November | 15 | 35 | 17 | 17 | 9 | 5 | 2 |
| December | 14 | 52 | 14 | 10 | 10 | - | - |
| Average percentage | 14 | 39 | 15 | 17 | 8 | 4 | 2 |

(b) Percentage frequency of storms intensifying into severe storms (in the Bay of Bengal and Arabian Sea) during different time intervals.

(Period of data - 1891 to 1970)

| | 0-12 hrs. | 12-24 hrs. | 24-36 hrs. | 36-48 hrs. | 48-72 hrs. | 72-96 hrs. | 96-120 hrs. |
|---|---|---|---|---|---|---|---|
| October | 30 | 23 | 23 | 18 | 6 | - | - |
| November | 22 | 30 | 17 | 17 | 9 | - | 5 |
| December | 40 | — | 40 | — | 20 | - | - |
| Average percentage | 31 | 18 | 27 | 12 | 12 | - | 2 |

Depressions develop into storms on 85% of occasions within 48 hrs of their formation; 12-24 hrs is the most common time interval (40% of cases). Cyclonic storms reach severe intensity within 36 hrs in 75% of occasions. While only 14% of depressions develop into cyclonic storms within 12 hrs, it will be noticed from the table that 31% of cyclonic storms became severe within 12 hrs. This brings out the rapid deepening of the storms.

3.4 The average life period of a storm/depression in the Bay of Bengal is 5 days in October, 4 days in November and 3 days in December; in the

Arabian Sea* the corresponding figures are 5,5 and 4. Thus the average life period of storms and depressions in the Indian sea areas is in general about 4–5 days.

## 4. Structure of a Cyclonic Storm

### 4.1 Horizontal structure

4.1.1 Wind field

4.1.1.1 The fully formed cyclone has three well-defined components; they are

i) the 'eye'+ where the winds are nearly calm

ii) the wall-cloud region, where the strongest winds are noticed, and

iii) the outer storm area where winds decrease as we move out in a radial direction, though they may be still strong.

The difference in the wind distribution between a fully developed cyclone and a depression or a low pressure area is that while in a cyclonic storm, the strongest winds are close to the centre within about a degree or two, they may be farther away from the centre for a depression or low pressure area. The mean distribution of surface wind speeds in severe cyclonic storms in the Indian seas (Fig. 4.1) was given by Koteswaram and Gaspar (1956) by compositing a total of 629 ships' observations in the Arabian Sea and Bay of Bengal during the 30 year period (1925–54). The distribution of surface winds around a severe cyclonic storm in Arabian Sea as determined from aircraft reconnaissance flights during the IIOE period is given in

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* Arabian sea storms are very few in number, compared to those in the Bay of Bengal. Thus many of the statistics and other details discussed in this report are primarily based on data for Bay of Bengal. However, they may be taken to apply to Arabian Sea also in a general way.

+As regards 'eye', we have
i) the pressure eye – where the sea-level pressure is minimum
ii) the wind eye – where the wind is calm
iii) the radar eye – centre as determined by the pattern of rain echoes
iv) the satellite eye – where an apparent clear spot in the cloud mass is noticed.

There are inherent inaccuracies in each type of 'eye' report and these reports may not agree with one another.

Fig. 4.2. A few more instances are given in the discussion of typical cyclonic storms (in Sections 15 to 18 of this report).

4.1.1.2 According to the wind distribution, two types of cyclonic storms have been recognised. In one type, the concentration of the maximum winds in the region of the wall-cloud is very pronounced and the anticyclonic shear outside the ring of maximum winds is strikingly large. The wind peak is narrow. Hurricane force winds may extend only 35–45 kms from the centre and may fall off to 40 knots at a distance of 200 km. In the other type, the decrease of winds outside the wall cloud is gradual. Hurricane force winds may extend about 100 km from the centre while winds of speed 35/40 knots may spread out to 400 km or even upto 600 km.

4.1.1.3 The mathematical representation of the wind profile around a tropical cyclone (from the region of maximum winds outwards) is taken, with certain simplifications, to be of the form $Vr^{\alpha}$ = const. where $V$ is the wind speed at a distance of $r$ from the centre and $\alpha$ a constant. When the actually observed wind profiles are fitted with this formula, it is noticed that $\alpha$ takes values ranging from 0.2 to 0.6. These figures refer to aircraft reconnaissance observations into the tropical hurricanes in the Atlantic. Vanderman (1962) has suggested tangential wind speed profile as

$$v = C_1 r \qquad 0 \leq r \leq R_0$$
$$v = C_2 r^{-5/8} \qquad R_0 \leq r \leq R$$

where $R_0$ is the radius of the cyclone eye, $R$ is an outside mean radius of the cyclonic circulation and $C_1$ and $C_2$ are constants.

4.1.1.4 An analysis of observations of maximum* winds associated with cyclonic storms in the Indian sea areas during the last one century shows that 50% of the storms had winds of hurricane force in their circulation while in only 20% of the occasions, the winds were less than 50 knots. Winds exceeding 100 knots have also been recorded, the maximum being 140 mph (122 knots) in the Midnapore cyclone of

* These need not always necessarily be the strongest winds in the circulation.

October 1942. We have now satellite pictures of cyclonic storms from which the maximum winds can be inferred. These pictures show that in the post-monsoon storms, in nearly 50% of cases, hurricane force is reached, and in 10% of cases winds over 100 knots occur.

4.1.1.5 In the cyclonic storm area, the average angle of inflow (i.e. the angle at which winds cut the isobar) is about 20° to 30°. Over the Indian sea area the inflow angle is about 20° at a distance of 5° degrees (of latitude or longitude) away from the centre, but this gradually increases as we go towards the centre and reaches the highest value of about 35°. It may even reach upto about 40°, as determined by Blandford (1888). The highest inflow is in the forward quadrants (with respect to storm movement).

4.1.1.6 Eliot (1890 and 1944) has given the angle of curvature to be about 120° on an average, in the Bay of Bengal storms, except when a storm approaches the coasts of Andhra Pradesh, Orissa and West Bengal. With northeast winds in this part of the Bay, the bearing of the storm centre may be in any direction between southsouthwest and southeast. Eliot (loc.cit) cites the False Point Cyclone of September 1885 as an instance of such peculiar wind direction-centre relationship. The wind at False Point (Orissa coast) remained steady at northeast during the whole period of approach of the storm to within a few minutes before the calm area reached the station, when it shifted suddenly to northwest. As the storm advanced in a northwesterly direction to False Point the angle between the wind direction and the centre was throughout 90°.

4.1.1.7 The north/northeasterlies* along the east coast of the Peninsula during the post-monsoon season do not give a reliable indication of the storm centre, particularly if the storm is slightly away. Very often they may only

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* This is particularly so in respect of winds at very low levels (i.e. 900 m and below); hence some meteorologists use the 850 mb winds to fix the centre.

strengthen without much change in direction on the approach of a cyclonic storm. The wind direction is also steadier than on a normal day. Hence, a certain amount of caution has to be exercised in using the winds in the western quadrants to determine the centre, unless it is very clear that the winds in the western sectors utilised for determining the centre have come well within the grip of the storm.

4.1.1.8 The radial dimensions of cyclonic storms vary widely - from 50-100 km radius to 2000 km radius. To study the size of the cyclonic storms in the Indian sea areas, it was assumed that the outermost closed isobar in the surface isobaric field was representative of its size. The outermost closed isobar is nearly circular, or elliptical. An average diameter of the outermost closed isobar was measured when the storm was out at sea. The analysis of the data in respect of cyclonic and severe cyclonic storms of the post-monsoon season in the Bay of Bengal during the period (1951-1970) is given below:-

TABLE - III

Percentage frequency of mean diameter (in degrees) of cyclonic storms in the Bay of Bengal during October to December

(Based on data of 1951-1970)

| | Mean diameter (in degrees Lat./Long.) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | 10-11 | 11-12 | 12-13 | 13-14 | 14-15 |
| Percentage frequency | 5 | 8 | 6 | 8 | 17 | 13 | 12 | 6 | 12 | 6 | 6 | 1 |

(Total No. of observations - 128)

The storms have generally (on about 50% of occasions), a diameter of about 6-10° of lat. or long. (i.e. 600-1000 km). There is another maximum at 11-12° lat./long. The figures may be interpreted to mean that the Bay storms in the immature stage usually have a diameter of about 600-1000 km, while the larger (mature) ones have a diameter of 1100-1200 km. While the smallest storm was about 3°, the largest one had 14.5° diameter. The outermost closed isobar has generally a value between 1005 mb and 1011 mb.

4.1.2 Pressure field

4.1.2.1 The pressure field associated with a tropical cyclone is very intense. The most intense cyclone on record in the Indian sea area was the False Point (Orissa coast) Cyclone of September 1885 with a central pressure of 919 mb which was 2.7"(92 mb) below normal. Observations of the lowest pressure at or very close to the centre, recorded during the passage of storms, are usually included in the Annual Storm Accounts, and other reports of the Department, wherever such observations are available. These records for the period 1884 to 1971 were gone through and 96 such observations were collected in the cases of severe cyclonic storms. Of these, only 8 refer to Arabian Sea and the remainder to the Bay of Bengal. An analysis of these observations is given in Table IV.

TABLE - IV

Frequency of lowest* pressures associated with severe cyclonic storms in the Bay of Bengal and Arabian Sea (1884-1971)

| Months | Pressure in mb. 911 - 20 | 21 - 30 | 31 - 40 | 41 - 50 | 51 - 60 | 61 - 70 | 71 - 80 | 81 - 90 | 91 - 1000 |
|---|---|---|---|---|---|---|---|---|---|
| January | - | - | - | - | - | - | 1 | - | - |
| February | - | - | - | - | - | - | - | - | - |
| March | - | - | - | - | - | - | 1 | 1 | 1 |
| April | - | - | - | - | - | - | - | - | 4 |
| May | 1 | - | - | 3 | - | 2 | 6 | 4 | 3 |
| June | - | - | - | - | - | 1 | 1 | 2 | - |
| July | - | - | - | - | - | - | 1 | 1 | - |
| August | - | - | - | - | - | - | - | - | - |
| September | 1 | - | - | - | - | 1 | 1 | 2 | 2 |
| October | - | - | - | - | 1 | 3 | 4 | 6 | 8 |
| November | - | 1 | 1 | 1 | - | 6 | 3 | 4 | 10 |
| December | - | - | - | - | - | - | 1 | 4 | 3 |
| Total No. of cases | 2 | 1 | 1 | 4 | 1 | 13 | 19 | 24 | 31 |
| Percentage | 2 | 1 | 1 | 4 | 1 | 14 | 20 | 25 | 32 |

* Since the records do not specify that in all the cases these values were observed at the centre of the severe cyclonic storms, the central pressures might have been even lower.

4.1.2.2 The lowest pressure on record in the Indian sea area is 919 mb, recorded at False Point (Orissa coast) in September 1885. Barring the False Point Cyclone of 1885, very low pressures on record were in May and in November from which one may infer that these are the months of the most severe storms in the Indian sea areas. Table IV shows 55% of the storms had a central pressure of 980 mb or more, 35% of the storms between 960 and 980 mb and only in about 10% it was less than 960 mb. Using the minimum pressure – maximum wind relation given by the revised Fletcher's formula (vide para 4.1.2.4), it is seen that a central pressure of 960 mb roughly corresponds to 100 knots maximum wind, 980 mb to 80 knots, 990 mb to 65 knots and 1000 mb to 50 knots. Thus, in two thirds of the cases of severe storms, hurricane wind force was reached. Winds over 100 knots (central pressure 960 mb or less) occur on nearly 10% of occasions. These pressure-derived extreme winds are in fair agreement with the observed maximum winds discussed in para 4.1. The central pressure of 919 mb in False Point Cyclone will correspond to a maximum wind of about 135 knots.

4.1.2.3 Although the isobars are nearly circular in a storm field, there is a certain amount of asymmetry in the pressure distribution. The isobars in the outermost regions of the cyclonic storm may be deformed by weak pressure troughs. With reference to the track, the maximum pressure gradients are usually met in the right front quadrant.

4.1.2.4 The central pressure and maximum wind in the cyclonic storm are interrelated. The relation is expressed by Fletcher's formula in the form

$$V_{max} = 16\sqrt{P_o - P_c}$$

where $V_{max}$ = maximum wind in the circulation

$P_o$ = Value of outermost closed isobar (in mb)

$P_c$ = Central pressure (in mb)

Instead of the actual value of the outermost closed isobar, a constant value $P_o$ = 1010 mb can also be used with fairly good results. This equation has subsequently been modified slightly based on additional and more accurate data from reconnaissance aircraft and a modified equation is in use by the National Hurricane Centre, U.S.A. The modified equation is

$$V_{max} = 14\sqrt{1013 - P_c}$$

The maximum wind derived from Fletcher's formula is about $1\frac{1}{2}$ times the maximum cyclostrophic wind. According to Fletcher himself, the ratio of $1\frac{1}{2}$ times does not appear unreasonable, considering the fact that Fletcher's formula applies to the wind at a point, whereas the cyclostrophic wind is an average value over a certain distance. According to more recent studies also "gradient/or cyclostrophic balance, in general, is not achieved by a wide margin" in the field of tropical storms.

4.1.2.5 As shown in para 4.1.1.8, the outermost closed isobar has a value ranging from 1005 to 1011 mb, the mean value being 1008 mb. Thus by taking a constant value for $P_o$ = 1010 mb, Fletcher's formula should yield fairly good results over the Indian sea area.

4.1.2.6 In the storm warning message bulletins issued by the India Met. Department, the central pressure has to be indicated. Similarly anticipated maximum wind values are also required for warning purposes. The maximum wind associated with the storm could be determined utilising the satellite pictures; from these wind values, using Fletcher's formula, the central pressure can be determined.

4.1.2.7 In the wall-cloud region, the pressure gradient is maximum. It may reach 1 mb per 2 to 5.0 km in intense storms. Outside the wall-cloud, pressure gradient is considerably less and is small. According to a study by Koteswaram and Gaspar, 75% of the values of the pressure gradient (outside the eye-wall) is within the range 0.02 to 0.07 mb per mile (1.5 km).

## 4.2 Vertical structure

4.2.1 Along the vertical axis, the cyclonic storm may be divided into three layers. They are:-

i) the inflow layer in which there is a pronounced inward radial component, extending throughout the lower troposphere. The most pronounced inflow occurs in the planetary boundary layer (below 1 km).

ii) the mid-tropospheric layer where there is very little radial motion.

iii) the outflow layer in the upper atmosphere, which extends upto the top of the storm. The maximum outflow is near 200 mb.

4.2.2 The air that enters the storm circulation in the inflow layer rises along the wall-cloud and the rainbands; subsequently, it flows outward from the storm top and sinks some distance away. The markedly cloud-free zone around tropical storms seen in the satellite pictures is an evidence of sinking motion. A little sinking motion also takes place in the 'eye'. A time-lapse movie, based on ATS pictures, has "graphically demonstrated the cyclonic movement of low level clouds in the inflow layer and anti-cyclonic flow of the cirrus canopy in the outflow layer".

4.2.3 The following are the general characteristics of the vertical structure of a mature hurricane (prior to its recurvature into the extra-tropical westerlies):

i) The low pressure core of the cyclonic storm extends throughout the troposphere and into the stratosphere upto 27 km and possibly higher. The axis of the cyclonic storm is taken to be vertical for all practical purposes.

ii) The pressure gradient in the core (i.e. the maximum winds in the field of the cyclonic storm) decreases with height above 6 km, but a weak and diffuse low or a trough persists even in the stratosphere. The wind decreases very slowly with height upto about 500 mb and much more rapidly at higher elevations.

iii) The cyclonic wind vortex has its maximum diameter at the surface and remains nearly unchanged upto 6 km. It diminishes rapidly with height above 6 km, reaching a minimum size at the tropopause level. The extent of the vortex near the tropopause level is only about 1 or $1\frac{1}{2}$ degree even in the case of large storms.

iv) Anticyclonic flow dominates the hurricane circulation above 6 km, which reaches its maximum intensity between 12 and 16 km. This flow is usually broken up into two or more anticyclonic vortices which are asymmetrically situated with reference to the inner cyclonic vortex.

v) In the anticyclonic flow, wind speeds may reach 60–80 knots between 12 km and 15 km in intense storms. These strong winds in the upper troposphere may be inferred from the pronounced cirrus flow seen in satellite pictures of storms.

vi) The cyclonic storm has a warm core below 15 km and a cold core aloft. The warm core is generally 8°C to 10°C warmer compared to the surroundings.

4.2.4 There have been hardly any soundings in India close to or within the 'eye' of a tropical storm, but for a dropsonde ascent taken during the IIOE period. This dropsonde, and another ascent at Calcutta on 29 September 1971 at 1200Z when a severe cyclonic storm was about 50 km south of the station, are given in Figs. 4.3(a) and 4.3(b).

## 5. Climatology of Storms and Depressions in the Indian Sea Areas

5.1 The publication "Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea" published by the India Meteorological Department provides the tracks of storms and depressions since 1877, giving the climatological data for a period of nearly a century. From these storm tracks a number of derived parameters can be obtained, and their statistics can be worked out and utilised for operational work. A few parameters concerned with the formation, movement and recurvature of storms are already available in the above publication.

5.2 The main uses of the climatological data in operational work are:-

i) to indicate climatologically preferred areas (if any) for the formation of depressions and their intensification into storms and severe storms,

ii) to provide climatological tracks as a basis for forecasting the future movement of systems.

From these points of view, some climatological aspects of the storms and depressions over the Indian sea areas, supplementing those already available in the departmental Storm Track Atlas and the papers by Rai Sircar (1955) and Ray Choudhary et al. (1959) are presented in the following paragraphs.

### 5.3 Monthly frequencies of storms and depressions

5.3.1 The total number of tropical storms and depressions that developed over the Indian sea areas is given below monthwise (Table V); each month has been sub-divided into two halves (1st to 15th of the month and 16th to the last day of the month). The computations have been split into three periods (i) 1877*-1890 (ii) 1891 to 1960 and (iii) 1961 to 1972. The last period 1961-1972 is a period when satellite data was available; in some cases we also had aircraft reconnaissance into the storms. So the location as well as the intensity of the tropical systems is much better documented during this period than what had been possible earlier. A comparison between the figures for 1961-1972 and the earlier periods brings out deficiencies in the statistics for the earlier period owing to lack of observations.

* As a matter of historical interest, it may be mentioned that available accounts of selected cyclones prior to 1877 go backwards as far as 1648.

TABLE – V

Statistics of cyclonic disturbances that formed in the Bay of Bengal and the Arabian Sea during the months of October to December

| Month | Period | Depression | | | Storm | | | Severe Storm | | | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1–15 | 16–31 | Total | 1–15 | 16–31 | Total | 1–15 | 16–31 | Total | |
| I. Bay of Bengal | | | | | | | | | | | |
| Oct. | 1877–90 | 5 | 4 | 9 | 3 | 5 | 8 | – | 2 | 2 | 19 |
| | 1891–1960 | 30 | 27 | 57 | 15 | 17 | 32 | 10 | 11 | 21 | 110 |
| | 1961–1972 | 6 | 7 | 13 | 1 | 1 | 2 | 1 | 7 | 8 | 23 |
| | Total ... | 41 | 38 | 79 | 19 | 23 | 42 | 11 | 20 | 31 | 152 |
| Nov. | 1877–90 | 5 | 3 | 8 | 2 | 3 | 5 | – | 3 | 3 | 16 |
| | 1891–1960 | 15 | 12 | 27 | 25 | 8 | 33 | 16 | 12 | 28 | 88 |
| | 1961–1972 | – | 2 | 2 | 1 | 2 | 3 | 9 | 3 | 12 | 17 |
| | Total ... | 20 | 17 | 37 | 28 | 13 | 41 | 25 | 18 | 43 | 121 |
| Dec. | 1877–90 | 2 | – | 2 | 2 | 2 | 4 | 1 | – | 1 | 7 |
| | 1891–1960 | 10 | 8 | 18 | 7 | 9 | 16 | 7 | 3 | 10 | 44 |
| | 1961–1972 | 2 | 2 | 4 | 2 | – | 2 | 4 | 2 | 6 | 12 |
| | Total ... | 14 | 10 | 24 | 11 | 11 | 22 | 12 | 5 | 17 | 63 |
| II. Arabian Sea | | | | | | | | | | | |
| Oct. | 1877–90 | – | – | – | – | – | – | – | – | – | – |
| | 1891–1960 | 4 | 3 | 7 | 1 | 9 | 10 | 3 | 1 | 4 | 21 |
| | 1961–1972 | 1 | 1 | 2 | 1 | – | 1 | – | 2 | 2 | 5 |
| | Total ... | 5 | 4 | 9 | 2 | 9 | 11 | 3 | 3 | 6 | 26 |
| Nov. | 1877–90 | – | – | – | – | – | – | – | 1 | 1 | 1 |
| | 1891–1960 | 3 | 2 | 5 | 2 | 1 | 3 | 6 | 2 | 8 | 16 |
| | 1961–1972 | 1 | 1 | 2 | – | 1 | 1 | 1 | – | 1 | 4 |
| | Total ... | 4 | 3 | 7 | 2 | 2 | 4 | 7 | 3 | 10 | 21 |
| Dec. | 1877–90 | – | – | – | – | – | – | – | – | – | – |
| | 1891–1960 | 1 | – | 1 | 1 | – | 1 | – | – | – | 2 |
| | 1961–1972 | – | – | – | 2 | – | 2 | – | 1 | 1 | 3 |
| | Total ... | 1 | – | 1 | 3 | – | 3 | – | 1 | 1 | 5 |

5.3.2 Some of the main features which are revealed by the statistics are as follows:

i) Within the post-monsoon season, the month of October has more storms and depressions than the other two months (November or December); ~~in the Bay of Bengal~~ on an average the frequency ~~of storm~~ is two in October in the Bay. There is a decrease in November, the decrease becoming considerable by December, when the frequency is just half the figure for November. In November, cyclonic and severe cyclonic storms are more in the first half of the month than in the latter half. Thus, we find that the earlier half of the post-monsoon season constitutes a major storm season for India.

ii) The number of storms and depressions in the Arabian Sea is very small compared to the Bay of Bengal, the ratio being about 1:4*.

iii) In October, in the Bay, depressions are slightly more in number than cyclonic storms and severe cyclonic storms; in the subsequent months, storms are more numerous than depressions. In particular, if we consider the statistics for the period 1961–1972, when satellite pictures were available, it is observed that storms far out-number depressions in November and December. Similarly, severe cyclones are more numerous than cyclonic storms. Thus, it would appear that depressions that form in the Indian sea areas in November and December have a very high chance of reaching the storm/severe storm stages.

### 5.4 Regions of formation of storms and depressions

5.4.1 The positions where the depressions were first located on the charts, where the depressions intensified into cyclonic storms and where they further intensified into severe cyclonic storms are given monthwise in Figs.5.1(a) to

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* The statistics given in Table V pertain to storms and depressions for which tracks have been published in "Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea: 1877–1960" which does not contain all cases (ref. para 3 of the Introduction to the Atlas). The ratio 1:4 given here is based upon all cases including those whose tracks have not been published.

5.1(i). The mean monthly sea surface isotherms* are also drawn on these charts, so that the climatologically favourable regions for cyclogenesis and intensification in relation to sea surface temperature distribution can be studied. The main features of these charts are discussed below, monthwise. The discussions relate mainly to the Bay of Bengal. The Arabian Sea is only briefly touched upon, in view of small number of storms/depressions in that area, and also because of the uncertainty in their positions (particularly in the western Arabian Sea) due to lack of data.

(a) October: (Figs. 5.1(a) to 5.1(c)

i) The whole of the Bay of Bengal is susceptible to cyclogenesis. When the statistics are considered for the first half and the second half of the month separately (Figs. 5.2(a) and 5.2(b)), we notice that during the first half, depressions form mostly to the north of 13°N; only 25% of them form to the south of 13°N. In the second half of the month, the region of formation of depressions is almost exclusively confined to south of 15°N. Even to the south of 15°N, the area between 9°N and 15°N, west of 87°E ~~seems to generate more depressions~~ has a higher density than the other areas. It is also possible that some of the depressions of the early part of October may be of the monsoon type.

ii) The western portion of the Bay (i.e. northwest, west central and the adjoining south Bay) ~~are~~ is the place where the intensification into a storm takes place.

iii) In the Arabian Sea, most of the depressions form in the eastern half, a large majority of them to the east of 70°E.

iv) Over the entire Bay, the monthly mean sea surface temperatures are above 27.8°C(82°F). The regions where depressions intensify into cyclonic storms, have a slightly higher sea surface temperature (28°.3 to 28.9°C i. 83° to

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* From "Monthly charts of Mean, Min. and Max. sea surface temperature of the Indian Ocean", Special Publication, SP-99, 1967 (reprinted 1968), published by U.S. Naval Oceanographic Office, Washington, D.C.

84 °F). In the Arabian Sea, the region where depressions form and intensify into storms have a water temperature of 27.8°C to 28.3°C (82° to 83°F).

(b) November: (Figs. 5.1(d) to 5.1(f)

i) In November, depressions form in the Bay only to the south of 15°N. Even here, the area to the west of 90°E i.e. southwest and adjoining southeast Bay, has more depressions than the area to the east. Intensification into cyclonic and severe cyclonic storms, is almost exclusively to the west of 90°E.

ii) In the Arabian Sea, the formation of depressions is mostly in southeast Arabian Sea; the area of their intensification, however, is much more spread out.

iii) Most of the Bay has a mean sea surface temperature of over 26.7°C (80°F). Depression formation is mostly over area with sea surface temperature about 27.8°C (82°F). In the Arabian Sea, the region of formation of depressions has a temperature of 27.8°C (82°F). Intensification of storms in the Bay is generally over areas of sea surface temperature between 27.8°C to 28.3°C (82° and 83°F).

(c) December: (Figs. 5.1(g) to 5.1(i)

i) During this month, storms and depressions develop only in the Bay. Their number in the Arabian Sea is negligible.

ii) Even within the Bay of Bengal, depression formation is only in the south Bay, with practically no formation in the rest of the Bay and Andaman Sea. More depressions form to the south of 10°N than to the north of it.

iii) Depression formation and intensification are mainly over sea areas with temperature greater than 26.7°C(80°F).

iv) As we progress from October to December, the region of formation of depressions also shifts to lower and lower latitudes.

5.4.2 The climatologically favourable areas of depression formation described above agree well with the location of the seasonal trough during the different months over the Indian sea areas. Thus, the low level trough configuration and areas of sea surface temperature more than 27.8°C(82°F) in October and November and above 26.7°C(80°F) in December are favourable areas for depression formation. Intensification of the depression into a cyclonic storm also occurs over areas of sea surface temperature above 28.3°C(83°F) in October, 27.8°C(82°F) in November and 26.7°C(80°F) in December. These climatological results have been amply borne out by day-to-day synoptic experience also.

5.4.3 It is also seen that very rarely a depression or storm has formed to the south of Lat.5°N. This is because the value of the Coriolis parameter should be larger than a certain minimum value for depression/storm formation.

5.4.4 Whenever weather is disturbed over areas climatologically favourable for the formation of storms and depressions, the forecaster keeps a special watch and is on the look-out for the earliest signs of the development of a depression/storm in the disturbed area. Similarly, when a low pressure area/depression is moving into an area climatologically favourable for further intensification, this by itself forms a basis for anticipating further development of the system.

### 5.5 Formation of storms and depressions in quick succession

5.5.1 It has been observed that, sometimes, storms and depressions form one after another in quick succession. An analysis of the past 82 years data (1891-1972) was made to study this aspect of the formation (Fig.5.3). In this analysis, storms and depressions are considered to form a "sequence" or "cluster" when they form at intervals not exceeding eight days. The main results of the analysis are:

i) Each "sequence" or "cluster" contains generally 2 to 3 disturbances. The maximum number of disturbances in a single "cluster" has been 5 (in the years 1891 and 1916).

ii) Usually the number of such 'clusters' in a season (Sept. to Dec.) has been 1 or 2; the maximum has been 3 (in 1946 and 1966).

iii) Out of the 82 years, there has been formation of depressions and storms in close sequence in 45 years and such formation has been observed to be more common in the earlier part (September and October) than in the latter part (during November-December) of the season.

iv) No periodicity has been revealed in the occurrence of these 'clusters'.

5.5.2 When the seasonal trough of low pressure over the Indian sea area becomes well-marked, it is often noticed that it remains so for sometime and during this period, low pressure systems form one after another in the trough and move westwards. Viewed against this synoptic feature, we can appreciate better the formation of storms and depressions in "clusters" discussed above.

## 5.6 Movement of storms and depressions

5.6.1 Statistics of the direction and speed of movement of storms and depressions are available in departmental Storm Track Atlas and the papers by Rai Sircar (1955) and Ray Choudhary et al (1959). The departmental Atlas gives the statistics for each $2\frac{1}{2}°$ squares, while Rai Sircar and Ray Choudhary et al. provide figures for every degree square. Rai Sircar also gives statistics for 10 day periods for certain months. In this respect, the statistics given by Rai Sircar and Ray Choudhary et al. are more detailed, and more useful for practical forecasting work.

5.6.2 The climatological tracks and statistics provide a basis for making a first guess for predicting the future movement of storms and depressions. The climatological track has to be judicially blended with the past 24-48 hours track, as well as the current synoptic and upper air information. In cases where data limitation is very severe, climatology is sometimes the only guide for predicting the track. In this connection, it is necessary to emphasise that over areas where the climatological statistics is based on too few observations, it is of very doubtful utility. The changes of a disturbance crossing different coastal belts having originated in a specified small sea area, are also given by Rai Sircar. This is a useful guide for issuing the two-stage warnings.

5.7 Disturbances crossing the Indian coasts

5.7.1 From the published tracks of storms and depressions for the period 1891 to 1970, the number of disturbances crossing the Indian coast or which came within a degree of the Indian coast line were determined. Frequencies of storms crossing coast at various latitudes in the different months were also worked out. (Table VI a. to VI d.)

TABLE - VI

Bay of Bengal

(a) Frequency of Depressions/Storms that crossed east coast of India or came within a degree of the coast during October-December (1891-1970).

| | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|
| 1. No. of depressions | 47 | 21 | 7 | 75 |
| 2. No. of storms | 20 | 17 | 3 | 40 |
| 3. No. of severe storms | 13 | 26 | 4 | 43 |
| | 80 | 64 | 14 | 158 |
| Total No. of disturbances that formed in Bay | 152 | 116 | 64 | 332 |
| % that crossed or approached the coast | 53% | 55% | 22% | |

TABLE – VI (Contd.)

(b) Frequency of depressions/storms crossing or coming within a degree of the east coast of India at various latitudes

| Between Latitudes | October | | | | November | | | | December | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dep. | Storm | Severe storm | Total | Dep. | Storm | Severe storm | Total | Dep. | Storm | Severe storm | Total |
| 22–21°N | 3 | 1 | 1 | 5 | 1 | 1 | – | 2 | – | – | – | – |
| 21–20 | 5 | 1 | 1 | 7 | – | 1 | 1 | 2 | – | – | – | – |
| 20–19 | 5 | 4 | 2 | 11 | – | 1 | 2 | 3 | – | – | – | – |
| 19–18 | 4 | 2 | 2 | 8 | 2 | 1 | 2 | 5 | – | – | – | – |
| 18–17 | 4 | – | 1 | 5 | 2 | – | – | 2 | – | – | – | – |
| 17–16 | 11 | 3 | 2 | 16 | – | 1 | 2 | 3 | 1 | – | 1 | 2 |
| 16–15 | 4 | 3 | – | 7 | – | 2 | 2 | 4 | 1 | – | – | 1 |
| 15–14 | 3 | 3 | 2 | 8 | – | 3 | 1 | 4 | – | – | – | – |
| 14–13 | 3 | 1 | – | 4 | 2 | 3 | – | 5 | 2 | – | – | 2 |
| 13–12 | 3 | 1 | 1 | 5 | 2 | 2 | 8 | 12 | – | 1 | – | 1 |
| 12–11 | 2 | – | 1 | 3 | 5 | 1 | 2 | 8 | 1 | – | 2 | 3 |
| 11–10 | – | 1 | – | 1 | 6 | 1 | 4 | 11 | 1 | 1 | – | 2 |
| 10–9 | – | – | – | – | 1 | – | – | 1 | 1 | 1 | 1 | 3 |
| 9–8 | – | – | – | – | – | – | 2 | 2 | – | – | – | – |
| | | | | 80 | | | | 64 | | | | 14 |

TABLE – VI (Contd.)
Arabian Sea

(c) Frequency of depressions/storms that crossed the west coast of India or approached within a degree of the coast during October–December (1891–1970)

| | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|
| 1. No. of depressions | 5 | 3 | 1 | 9 |
| 2. No. of storms | 3 | 4 | 1 | 8 |
| 3. No. of severe storms | 1 | 2 | – | 3 |
| Total | 9 | 9 | 2 | 20 |
| Total No. of disturbances that formed in Arabian Sea | 39 | 38 | 10 | 87 |
| % of disturbances that crossed or approached the coast | 23% | 24% | 20% | |

(d) Frequency of Depressions/storms crossing or coming within a degree of the west coast of India at various latitudes

| Between latitudes | Oct. | | | | Nov. | | | | Dec. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dep. | Storm | Severe storm | Total | Dep. | Storm | Severe storm | Total | Dep. | Storm | Severe storm | Total |
| 24–23°N | – | – | – | – | 1 | – | – | 1 | – | – | – | – |
| 23–22 | 2 | – | – | 2 | – | – | – | – | – | – | – | – |
| 22–21 | 2 | 3 | – | 5 | – | – | – | – | – | 1 | – | 1 |
| 21–20 | – | – | – | – | 1 | 1 | – | 2 | – | – | – | – |
| 20–19 | – | – | – | – | 1 | 1 | 1 | 3 | – | – | – | – |
| 19–18 | 1 | – | 1 | 2 | – | 2 | – | 2 | 1 | – | – | 1 |
| 18–17 | – | – | – | – | – | – | 1 | 1 | – | – | – | – |
| | | | | 9 | | | | 9 | | | | 2 |

5.7.2 It will be seen that so far as the Bay of Bengal is concerned, disturbances affecting the Indian coast constitute only 55% of the total number of disturbances that form in the Bay during October and November. In December, their frequency decreases to about 20%. In December, more than half the number of storms dissipate out at sea as they move north, one of the reasons for this being the colder and drier air and colder sea surface temperatures in north Bay during December.

5.7.3 Table VI(b) shows that as the season advances, storms and depressions strike the east coast at more southerly latitudes. In October most storms and depressions (80%) strike coast north of 14°N; in November 70% strike coast between 10°N and 16°N and in December 80% strike coast to the south of 14°N. While the east coast between 14°N and 21°N is very vulnerable for storms and depressions in October, in November it is between 10°N and 14°N. It also appears that certain coastal belts in between (such as between 17°N and 18°N) are relatively free from the storms and depressions.

5.7.4 Table VI(c) shows that only about 20–25% of the disturbances affect the west coast in all the three months. Of these, about 80% affect the coastal belt between 21°N and 23°N in October and about 80%, the coastal belt between Lat. 18°N and 21°N in November.

## 6. Differences between Cyclonic Disturbances

6.1 The basic difference between a depression, a storm and a severe storm lies in the maximum wind in its circulation as given in the fundamental definition in Sec.2. The classification of cyclonic systems in the departmental weather bulletins is, therefore, almost exclusively based on wind speed. In addition to wind speed, there are a few other differences also which we notice on the charts and these are given below:

### 6.2 Number of closed isobars

6.2.1 Low pressure areas are identified by a single closed isobar at 2 mb interval. Sometimes, it may be only an odd-valued isobar. There are generally

2 to 3 closed isobars around a depression, and 4 around deep depressions.

### 6.3 Pressure departures

6.3.1 A negative pressure departure of 5 mb or more is being taken as a favourable sign of the intensification of a tropical disturbance into a tropical storm. With reference to Bay of Bengal, Eliot formulated a negative departure of 6 mb to 7 mb as the lower limit for a cyclonic storm. From an examination of the synoptic charts for the recent years a statistics of distribution of pressure departures associated with low pressure areas, depressions and deep depressions was made and the results are given in the following Table VII.

TABLE - VII

Percentage frequency distribution of pressure departures from normal associated with Low Pressure Areas, Depressions and Deep Depressions in the Bay of Bengal and Arabian Sea during the months October to December (period of data - Depressions/Deep Depressions 1961-72; period of data - Low Pressure Areas 1967-71)

Percentage frequency

| Pressure Departure from normal (mb) | Low Pressure Areas | Depressions | Deep Depressions |
|---|---|---|---|
| + 2 | 5 | - | - |
| + 1 | 9 | - | - |
| 0 | 14 | - | - |
| - 1 | 32 | 5 | - |
| - 2 | 18 | 11 | - |
| - 3 | 12 | 16 | 5 |
| - 4 | 2 | 18 | 2 |
| - 5 | 8 | 22 | 26 |
| - 6 | | 14 | 21 |
| - 7 | | 7 | 14 |
| - 8 | | 5 | 16 |
| - 9 | | 1 | 9 |
| -10 | | | 5 |
| -11 | | | 2 |
| Total number of cases | 126 | 73 | 43 |

This table shows that nearly 75% of the low pressure areas have a pressure departure between 0 to –3 mb; 70% of depressions have a departure between –3 and –6 mb, while nearly 80% of deep depressions between –5 to –8 mb.

6.4 Wind field

6.4.1 The distribution of winds around the cyclonic storms is different from that of depressions. As we have seen in section 4, in a fully developed cyclonic storm, the strongest winds are concentrated in the wall–cloud region in the form of a ring and they decrease as we move outwards from the wall cloud. Certain amount of asymmetry of wind field is also noticed in cyclonic storms. In the case of depressions and low pressure areas, winds close to the centre are usually light, the higher speeds being further away from the centre/ central region. The asymmetry in wind field is also mere pronounced in depressions than in the cyclonic storms. It has been found that in the case of depressions, strong winds of the order of 30 to 40 kts may be sometimes noticed sufficiently away from the centre, in the region of heavy convection. Thus, it poses a critical problem to the forecaster viz. a more mechanical application of the criteria of wind speed given in Table I, should not be made. Other corroborative evidence also should be looked for before calling a disturbance as a cyclonic storm.

6.5 Upper air circulation

6.5.1 The upper air cyclonic circulation associated with low pressure areas hardly extends upto 850 mb. In the case of depressions, the circulation extends definitely upto 700 mb and often upto the mid–troposphere. Circulations associated with cyclonic storms extend still higher, though above 200 mb the areal extent of the circulation is very small and can hardly be seen within the synoptic network. At these levels, on the synoptic scale, we may recognise only an anticyclonic flow. The anticyclonic flow is most pronounced between 12 km and 15 km.

6.5.2 Depressions have an easily recognizable tilt with height; it is usually towards the south in the Indian sea areas. The tilt is less pronounced in deep depressions. In cyclonic storms, there is no tilt and for all practical purposes the axis is vertical throughout the troposphere.

### 6.6 Cloud structure and weather

6.6.1 According to Malkus (1958), the critical lower limit for 'eye' formation is about 45 mph (40 knots). In disturbances which are classed as cyclonic storms (34-47 knots), the 'eye' is in the process of formation. Thus, when an 'eye' becomes well-defined the maximum wind speed should reach hurricane force. Satellite nomogram also indicates that for Stage X Cat. 3 storms (in which 'eye' is not yet well-defined and circular) the wind speed is of the order of 65 knots even for a diameter of as small as 2 degrees.

6.6.2 One of the main differences in the cloud structure between a cyclonic storm and a depression or a low pressure area is that in the latter case the heavy clouding may be away from the centre. In some cases, weather may be relatively quiescent near the centre. This is borne out by satellite pictures of depressions and low pressure areas, where the central region is relatively less clouded or even cloud-free. Satellite pictures also show that the cloud mass is more amorphous in the weaker disturbances, and it gets organized as the intensity of the disturbance increases. The bands become very well-defined in a severe cyclonic storm.

## 7. Determination of the centre and intensity of cyclonic disturbances

7.1 The main steps involved before the issue of advisories and warnings for tropical disturbances consists broadly of the following:-

i) detection of the tropical cyclonic disturbance,

ii) determination of the centre of the disturbance and its intensity or stage of development,

iii) forecast of further development or weakening,

iv) forecast of future movement

Steps(i) and (ii) constitute what is known as the "analysis" of the current situation and steps(iii) and (iv), form the "prognosis". Based on the forecast intensity and track of the depression/storm, storm warnings are issued. To accomplish (i) and (ii), we should have an idea of the structure of the system in its various stages of development and this we have dealt with in Secs.3,4 and 6. The intensity and the stage of development of the disturbances can be assessed by recognizing the appropriate characteristics from the discussion in these sections. They also contain some aspects of the problem regarding the determination of the centre. In this section, we will briefly summarise the techniques used for determining the centres of the cyclonic disturbances. Steps (iii) and (iv) which form the forecast are dealt with in Secs. 8 and 9. A model check sheet for use in operational offices is given in Appendix II.

7.2 Low pressure areas do not have a recognizable centre. From the depression stage onwards, the centre can be uniquely fixed. The data used for fixing the centre are:-

i) ships' observations from the depression/storm field,
ii) upper winds in the field (upto 900 m.) from island and coastal stations,
iii) satellite pictures,
iv) radar echoes and
v) extrapolation of past track.

(i) Ships observations: Wind observations from ships are utilised for determining the centre of the depression/storm. For this, there should be a minimum of at least 2 or 3 observations around the system, if the observations are somewhat away from the centre. In the case of a cyclonic storm, even a single observation, if it is close to the centre, may give an idea of the location of the centre. In the field of a cyclonic storm, the angle of inflow is generally 20° at a distance of 5° of lat./long. away from the centre and increases to about 35° close to the centre. Regional peculiarities in wind distribution around a storm, such as those mentioned in paras 4.1.1.6 and 4.1.1.7 should be kept in mind while using ships' recorded winds. Some points regarding the use of ships' observations in the analysis of weather charts are given in Appendix III.

ii) Lower tropospheric winds: The lower tropospheric winds may also be utilised just like the ships' winds discussed in the previous para. In this connection, the circumstances where these winds may not be representative for determining the centres are discussed in paras 4.1.1.6 and 4.1.1.7; they will also be pointed out during the discussion of typical synoptic situations in Sec. 15 to 18.

iii) Satellite pictures: The use of satellite pictures in determining centres of storms/depressions will be discussed in detail in Sec. 10.

iv) Radar echoes: (a) when the 'eye' of the storm is within the range of the coastal radar station, the centre can be located. The location will be accurate when the 'eye' is small, circular and the eye-wall closed. Frequently, the eye-wall may not be completely closed and even if closed, it may be elliptical or irregularly shaped and the shape may also vary from hour to hour. In such cases, radar tracking may give irregular movement of the storm centre.

(b) When the 'eye' is not within the range of the radar, we may get some of the spiralband echoes, in the shape of equi-angular spirals. By using suitable spiral overlays with well-defined spiral band echoes, the involuting spiral echo can be extrapolated and the centre determined. The accuracy of determination by this method is best when a band subtending an arc of more than 180° appears on the scope. Some studies in U.S.A. have shown that the storm centre could be located by this method within a radius of 28 kms in 83% of the cases studied, while some others have given a median error of about 30-40 kms.

(c) 'Eye' positions determined by radar have revealed oscillation in the path and even looped paths in some cases.

v) Extrapolation of past track: The past track of the storm can be extrapolated to the current synoptic hour on the basis of the forecast movement during the preceding 12 or 24 hrs. This extrapolated position may form a first guess in the centre fixation, which can be modified in the light of the actual observations as discussed in (i) to (iv) above.

## 8. Development of Cyclonic Storms

8.1 In this section we describe the meteorological conditions that are favourable for the development of cyclonic storms in general and with special reference to post-monsoon season. These conditions are necessary, though not necessarily sufficient, for cyclone formation, but it is not yet known what weightage should be given to each condition. A favourable combination of a number of conditions is to be carefully watched for the development of depressions and cyclonic storms, and their intensification. In the present state of the subject, in our country, tropical storm forecasting is still largely based on subjective reasoning, and available data.

8.2 A cyclonic storm appears initially either as a low or a depression in areas of weak pressure gradient and light winds. Over the Indian sea areas an initial low or depression usually forms in the seasonal trough, which may extend from the Arabian Sea to southwest Pacific across the Bay of Bengal. Some of the synoptic features noticed prior to the formation of a low/depression are discussed in the following paragraphs.

### 8.3 Intensification of the seasonal trough

8.3.1 Prior to the formation of a low or depression the seasonal trough becomes well-marked and may extend across a large longitudinal belt from west to east. It may extend from the west Arabian Sea to southwest Pacific across the south Bay. A number of cyclonic vortices may be embedded in the trough; often these vortices are spaced at nearly equal longitudinal intervals. The westerlies to the south of the trough or the ~~easterlies~~ northeasterlies/easterlies to the north of the trough or both the streams may strengthen. Such strong wind belts are usually well to the south or north of the trough line, so that a region of well-marked cyclonic shear appears in the trough zone. The trough also extends into the mid-tropospheric levels. Thus the strengthening of the winds on both or either side of the seasonal trough indicates potential disturbed conditions. If the initial weak disturbances that form in the seasonal trough are slow moving or quasi-stationery, such disturbances are more likely to develop than the fast moving ones.

### 8.4 Movement of a low pressure system from the east across Burma or Malay Peninsula

8.4.1 Cyclonic systems in the southwest Pacific travelling in a westerly direction cross into the Andaman Sea and the Bay of Bengal. Most often they reach the Indian seas as low pressure areas. Sometimes they may be seen only as a travelling 24 hour pressure change or negative pressure departure field. At other times, it is only a circulation in the lower and/or middle troposphere that is noticed. Only very occasionally, the low pressure systems from the east enter the Bay/Andaman Sea as depression. Similar features are also noticed in the case of disturbances from the Bay emerging into Arabian Sea after crossing the Indian Peninsula or Sri Lanka.

8.4.2 The typhoons that travel in a direction between west and northwest and strike the coast of south China or the Indo-China Peninsula are fairly large in number in September and October. Correspondingly, the frequency of storms and depressions that develop over the Bay under the influence of these low pressure systems from the east is also a maximum in September. Their number in October, though less than in September, is still significant. By November, such storms considerably decrease in number; one of the reasons being that the number of typhoons in the China Seas decreases considerably in this month. In terms of a ratio between the number of typhoons striking India-China coast and the number that influence weather in the Indian sea area, October and November are nearly equal. In December, such instances become very small in number.

8.4.3 Taking the post-monsoon season as a whole, the origin of a little over 50% of the storms and depressions in the Bay of Bengal can be traced to the southwest Pacific. Similarly, about 50% of the storms and depressions in the Arabian Sea can be connected with earlier systems in the Bay of Bengal. In a good number of these cases, the Bay systems move across the south Peninsula as depressions and emerge into the Arabian Sea.

8.5 Pressure changes and departures

8.5.1 In the tropical oceanic areas as a whole, whenever the 24 hour pressure fall, in association with low pressure areas/waves and localised in areal extent, reaches the order of 3 mb or more, development of a tropical storm is indicated. Similarly pressure values 5 mb or more below normal (localised in areal extent) is considered as a sign of probable cyclonic storm.

8.5.2 With reference to Bay of Bengal, Eliot (1890 and 1944) has formulated that if the pressure is 2/10"(6-7 mb) below normal, it is practically certain that a cyclonic storm has formed and if 0.15"(5 mb) below normal the probabilities are at least 3 to 1. Similarly if the pressure falls by 2/10" (6-7 mb) or upwards in 24 hrs, it is almost practically certain that a cyclonic storm is approaching the place. Gray (1968) also mentions a negative pressure departure of 5 mb or more as a sign of the growth of tropical disturbances into tropical storm intensity.

8.5.3 If 24 hrs pressure change and pressure departure isopleths are carefully drawn over sea areas, they may be useful in detecting areas of cyclogenesis and also in predicting the motion. When ships' observations are sufficient in number, isobars can be drawn over the sea areas with good confidence and it is possible to construct the 24 hour change and pressure departure isopleths over the sea areas fairly objectively. If a register of corrections for ships bar readings is maintained in each Forecasting Office, it greatly facilitates the isobaric analysis over the sea areas, particularly on days of disturbed weather.

## 8.6 Sea Surface Temperature

8.6.1 A sea surface temperature of 26°C–27°C is the threshold value below which intense cyclones are unlikely to form. It is mentioned in literature that the warmer the sea surface, the more intense is the cyclonic storm (i.e. deeper is the central pressure). Rapid deepening has been found to be associated with sea surface temperature equal to or higher than 28°C. The warmer the sea surface, the higher may be the rate of pressure fall.

8.6.2 A sea surface temperature of 27°C will ensure that the saturated air lifted from the lowest atmospheric layers with about the same temperature as the sea, and also expanded moist adiabatically, will remain considerably warmer than the surrounding undisturbed atmosphere at least upto about 200 mb. The mean vertical distribution of temperature over the Indian sea areas is such that an air parcel with a temperature ~~at~~ of 27°C or more at the sea level (roughly 1000 mb) and ascending at moist adiabatic lapse rate will always remain warmer than the environment, the buoyancy increasing with height as we go up (see Fig. 8.1).

8.6.3 According to a recent work, the warm sea water "should be deep, rather than a surface film, if the supply of energy to a storm is to be sufficient, to produce true hurricane intensity".

8.6.4 Rapid weakening of tropical cyclones as they move over to colder waters or inland is also attributed largely to the removal of the heat source provided by the warm oceans.

8.6.5 The representativeness of sea surface temperature observations recorded by the various methods and the systematic differences between them are being studied intensively nowadays. One of the results has been that "intake temperatures on an average, were 0.3°C warmer than temperatures measured by bucket".

### 8.7 Weak vertical wind shear

8.7.1 Another favourable factor for storm formation is the weak vertical wind shear in the basic current. Studies in the case of hurricanes in West Atlantic have shown that "within a radius of 4 degrees of latitude, the vertical shear must not exceed about 15 kts, if the disturbance is to grow". (Here the shear has been taken between the mean lower tropospheric winds (1000–600 mb) and the mean upper tropospheric winds (600–200 mb). The small shears ensure that the latent heat released by the cumulus convection is not carried away by the strong winds and diluted but concentrated over a small area. This warming of the atmosphere over a limited area will initiate the fall of the surface pressure and produce a chain reaction. High thickness values in the mid- and upper troposphere (500–200 mb) indicate warming and hence are favourable for the development of the surface pressure system. In view of the lack of adequate upper air data, it is difficult to determine the wind shears, thickness values etc. over large portions of Arabian Sea and Bay of Bengal.

### 8.8 Upper divergence

8.8.1 A divergence in the upper troposphere (300 mb, 200 mb and above) is often looked into for the initial formation of the cyclone. The upper divergence is provided by such upper air patterns as, a high pressure cell, anticyclonic curvature of wind flow, approaching trough etc. In view of the sparse upper air observations over sea areas, it is often difficult to locate these systems on the operational charts with the desired amount of objectivity. Satellite-derived upper winds and geopotential heights and aircraft reports provide very valuable data in the analysis of upper tropospheric charts over the sea areas.

8.8.2 However, there is a school of thought that upper level divergence is not a necessary pre-condition for storm development. They take the support of the CISK (Conditional Instability of Second Kind) hypothesis to explain the pressure fall as a result of upper warming caused by the cumulus convection; hence another divergence (to cause the pressure fall in the initial stages) is not considered necessary, though their presence may provide an additional mechanism for the initial pressure fall.

8.8.3 Often strong jet streams have been noticed a few degrees poleward of the cyclonic storm. Satellite pictures have brought out the existence of such jet streams in a picturesque way, the jet stream cloud being linked with the outflow from one of the quadrants of the storm. Such an upper air system provides the necessary mechanism to remove the excess heat from the storm area to the other regions; consequently, this is considered favourable for the maintenance of the storm.

## 8.9 Weather

8.9.1 Tropical storms generally develop out of initial weak disturbances which are associated with heavy convection. The necessity of heavy Cb for storm development has been brought out by the CISK theory. Aerial reconnaissance in the field of tropical storms has provided observational evidence of the presence of heavy Cb, sometimes referred to as a "hot tower". Indian meteorologists in early days used to lay much stress on squalls and heavy thunderstorm out at sea, as being the precursors of cyclonic storms. Eliot mentions that "during the period of change from slightly unsettled and threatening weather to the formation of a storm more or less dangerous to shipping, one of the most important and striking points is the increase in the numbers and strength of squalls which are an invariable feature in cyclonic storms from the very earliest stages". Therefore, weak disturbances associated with unusually heavy Cb activity should be watched for potential storm formation. Heavy rainfall or heavy (and very bright) clouding concentrated over limited areas in satellite pictures should be taken to be indications of unusual Cb activity. Steady rainfall at several adjoining stations with cirrostatus and altostratus overcast (when it is not the seasonal weather over the area) and particularly when they persist over a few consecutive synoptic charts of the day, is also taken to be a precursor of tropical storm formation.

### 8.10 Satellite cloud pictures

8.10.1 Increasing cirrus streamers and their appearance in more and more sectors (as seen in satellite pictures) are indicative of increasing mass outflow from the upper levels over the storm area; this is a useful indication of the intensification. Similarly the cloudmass and the bands become better organised as the system develops. Recently, it has been reported that prominent bands emanating from the south and feeding into the cyclonic storm are very favourable indications of development. These bands are called "feeder bands" and "they appear to represent the core of inflow channel". Pronounced "feeder bands" emanating from low latitudes (5° or more in length) are rated high as an indication of rapid development.

### 8.11 Sea and swell

8.11.1 Sea and swell observations are useful as signs of existence of a storm which has already formed. The wave heights give an approximate measure of the wind strength out at sea. The swells travel much faster out of the storm field than the storm itself and thus provide an early indication at distant places. The direction of the swell outside the storm area is indicative of the bearing of the storm centre. It is usually a little to the left of the bearing of the centre. Swell can be distinctly felt even when the storms are 400 miles away. This is especially the case in the northern and western quadrants. Swells become higher and more confused as the storm approaches. Thus the wave observations can be utilised to supplement other data.

### 8.12 Microseisms

8.12.1 Microseisms also give indication of presence of storms out at sea. Storm type microseisms have been discussed in detail in FMU Report No.IV-16.

8.13 If one or more of the above-mentioned features are noticed on any day on the synoptic charts, the area should be kept under surveillance for probable existence of a depression or storm , and their further development. In addition to this, satellite and radar reports over the area should be carefully examined. If any disturbance is expected to move into areas favourable for development as discussed above, a further intensification of the system may be anticipated.

### 9. Movement of Tropical Storms and Depressions

9.1 The prediction of the movement of tropical storms is a very important but difficult task. On the forecast position of the track for the next 24 to 48 hrs, depends the entire warning work. The present techniques used in the department for prediction of the movement is almost entirely subjective, and is largely dependent on the experience and the skill of the forecaster. A judicious combination of climatology, extrapolation of the past 24–48 hrs track, evaluation of the basic steering current and the current indications on the synoptic charts, together with a few empirical rules, form the basis of prediction rules for the movement of storms.

#### 9.2 Climatology and extrapolation

9.2.1 Climatology of past storm tracks is one of the most useful tools in forecasting the movement of storms and depressions. Particularly in early stages, when the storm is far out at sea in a data-void area and has not yet influenced the coastal circulation, and where the storm track has not been long enough to extrapolate, climatology is the only aid to fall back upon. The departmental storm track atlas and the climatological studies of storms and depressions by Rai Sircar and Ray Choudhary et al provide a very useful analysis of the most likely direction and speed, when a storm is situated in a particular degree square. This, together with the extrapolation of the earlier 24 to 48 hrs track, provides an initial guess which the forecaster can further refine taking into account the current synoptic and upper air conditions.

9.2.2 The climatological atlases give frequencies of movement in various directions in every $2\frac{1}{2}$ or 1 degree square. In squares where the modal direction is quite well-marked, the direction forecast is likely to yield a good result but where good modal values do not exist and the climatological directions are distributed over a large number of points of the compass, this method should not be given much weightage. Squares where the statistics is based on a large number of observations should yield better results than those where the number of observations is very small. Similarly climatological values of speeds could also be used. The probability statistics regarding the ports near which the storm is likely to cross coast (given by Rai Sircar) can be advantageously used to frame the first stage warnings.

9.2.3 Based on climatology and persistence, computerised forecasts of movement are now being issued; at present there are two types of such forecasts – one giving equal weightage to climatology and persistence and the other giving a variable weightage. A forecast based on climatology and extrapolation is likely to be very much out during the stages of recurvature, sudden acceleration and retardation of the storm.

## 9.3 Steering

9.3.1 This concept involves that the storm is steered by the basic current in which it is embedded. The problem here is to distinguish the basic steering current which directs the storm motion, from the storm circulation and to use it to determine the future storm movement. Regarding the steering concept, opinion is strongly divided on the point concerning what levels constitute the steering levels, and how it is related to storm movement. The broad ideas in vogue are:-

i) The high level flow (200 mb - 150 mb levels), constitutes the steering current and the flow at these levels determine the future storm movement.

ii) The steering current is also defined by some other workers as the pressure weighted mean flow from the surface to 300 mb (i.e. the levels in which the storm circulation is present) and extending over a band 8° of lat/long width and centred on the storm.

iii) The average steering current is the flow in the layer from 500 mb to 200 mb.

iv) The U.S. Navy, in one of the recent reports, claims that the prognostic 700 mb flow is found to give the best results of steering.

v) In recent investigations in the Indian sea areas, the pressure weighted mean winds of 500 mb, 300 mb and 200 mb levels was reported to give a better estimate of the direction of movement of storms than the wind at any of these individual levels. The weights used are 3, 4 and 3 respectively and they have been determined empirically.

9.4 Pressure changes

9.4.1 Petterssen (1940) developed a simple kinematical relationship on the movement and development of well-defined pressure systems. These formulae are applicable only in cases where

i) the analysis is reliable and simple,

ii) the conditions are such that differentials may be replaced by suitable finite differences, and

iii) the acceleration is a minimum.

Since the pressure distribution in the field of a tropical storm is well-defined and has a large gradient, the isobaric configuration, pressure changes and their gradients may constitute an objective and reliable aid for forecasting storm movement. However, in the absence of sufficient ships data, the isobaric delineation over the sea areas and their spacing are very uncertain. When the storm comes near the coast, pressure changes at coastal stations are very valuable. Here again it is claimed that the 3 or 6 hourly pressure changes (corrected for diurnal variation) are superior to 24 hour pressure changes.

9.5 Broadscale upper air flow patterns

9.5.1 Certain well-defined upper air flow patterns in the middle and upper troposphere have been found to be related to the direction of movement of the storm and, consequently, have some forecasting value. The very well-known feature is the recurvature of tropical storms when they come under the influence of an eastward moving westerly trough. According to Dunn and Miller*, the typical

* "Atlantic Hurricanes" by Gordon E. Dunn, Director, National Hurricane Center and Banner I. Miller, Research Meteorologist, National Hurricane Center, pp.188 to 189.

flow patterns associated with recurvature and non-recurvature are:-

(a) <u>Recurvature:</u>

i) Large-amplitude troughs, extending southward from the westerlies and located within a few hundred miles to the west of the centre.

ii) Well-marked low latitude trough building northward into the westerlies.

iii) Weak trough between two separate subtropical high cells.

(b) <u>Non-recurvature:</u>

i) A strong sub-tropical HIGH to the north of the storm, with the major trough in the westerlies located far to the west of the longitude of the storm.

ii) Westerlies flat, i.e. waves having very small amplitude, and at latitudes at or north of normal.

9.5.2 The trough pattern changes amplitude and intensity, as short wave troughs move through a slow moving long wave. As a result when the amplitude of the westerly trough does not remain large but rapidly decreases, the recurvature may not be complete but there will be only a temporary change in direction towards the north, and the storm will once again continue in a westerly direction after the westerly trough dampens.

9.5.3 When the subtropical anticyclone in the upper troposphere is well to the north of the storm track and the storm is moving in a broad and deep easterly flow, the track is likely to be only in a westerly direction. But, when the storm crosses the sub-tropical ridge line, and moves into the belt of westerlies, the storm acquires an easterly component of motion.

9.5.4 Result of a study of the 200 mb flow patterns vis-a-vis the storm tracks during the past 5 years are given in Table VIII below:

## TABLE - VIII

Percentage frequency of direction of movement of cyclonic storms in the Bay of Bengal during October to December associated with different positions of the ridge line at 200 mb level (Based on data for 1967 - 1971)

Direction of movement of storms

| Storm positions with respect to ridge line at 200 mb. | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW | Stationary |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| More than 3° north | | 50 | 34 | 8 | 8 | | | | | | | | | | | | |
| Within 3° north | 12 | 21 | 30 | 5 | 5 | | | | | | | 5 | | | 17 | | 5 |
| Within 3° south | 28 | 11 | 2 | | | | | | | | 7 | 2 | 2 | 18 | 15 | 4 | 11 |
| More than 3° south | 6 | 8 | 2 | | | | | | | | | 6 | 12 | 44 | 22 | | |

(Number of Observations - 131)

It is seen from the above table that

i) when the storm was 3° lat. or more to the south of the ridge line, the storm moved in a westerly/northwesterly direction in 80% of the occasions

ii) when the storm was within 3° of latitude of the ridge line, the movement was towards the north; (when the storm is close to the ridge line, the movement may be slow and the storm may be even stationary) and

iii) when the storm crossed well to the north of the ridge line, the storm continued to move in a northerly direction and subsequently, when it moved into well defined westerlies, the track had an easterly component. With the expanding network of R.S. and R.W. stations and the availability of satellite-derived upper winds, and reports from jet aircraft, the delineation of the subtropical ridge line over the oceanic area is becoming more satisfactory and objective. Thus, the 200 mb ridge line location may give a clue for forecasting the movement.

9.6 In addition, other parameters such as thermal advection etc. have been advocated by some workers.

9.7 The final decision to be taken by the forecaster on the movement will, therefore, depend upon all these features and a judicious combination of all the parameters has to be made. The weightage to be given to the various parameters will depend on the situation. For instance, when the current synoptic and upper air flow patterns strongly suggest a particular direction and when this direction is at variance with the climatological track, it would not be advisable to give weightage to climatological tracks.

## 10. Satellite Picture Data in the Location and Estimation of the Intensity of Tropical Storms and Depressions

10.1 Satellite pictures provide the best coverage of tropical disturbances. With the satellite pictures now available on a routine basis at the forecasting offices, there is no possibility of any depression or storm being missed due to lack of conventional observations.

10.2 Detailed literature exists on the interpretation of the satellite pictures of tropical disturbances to locate the centre of the system and its intensity. The system adopted by India Meteorological Department for the classification of satellite pictures of tropical disturbances is the same as the one currently in use at the NESC, Washington*. The nomogram (Appendix IV) developed in this connection, provides the maximum winds anticipated in the field of the cyclonic storm; utilising Fletchers' formula, the central pressure can be arrived at.

10.3 Experience with satellite data is that the satellite derived maximum winds using the nomogram are satisfactory over the Indian sea areas. In the following paragraphs, a few guidelines on the use of satellite pictures in operational work will be indicated.

10.4 Satellite information should be judiciously blended with other types of

* Since 1972,NESC has adopted a different system of classification of satellite pictures of tropical disturbances (Ref. NOAA Tech.Memorandum NESS 45).

observations – from ships, ground stations, radar reports, aircraft reports etc. – to get the best integrated picture of the tropical disturbance. Unless such conventional observations are available close to the depression/storm centre, and they provide conclusive information, maximum weightage should be given to the satellite observations, both with regard to its centre and intensity.

10.5 The estimations from satellite pictures relate to (i) centre of the storm and (ii) the intensity of the system. To make the best use of satellite data, forecasters should also be aware of the limitations of the satellite pictures in these estimations and the order of magnitude of errors involved in them.

## 10.6 Centre determination

10.6.1 When the "eye" is seen in the picture or when the bands are well-defined so that by following the bands the centre may be determined satisfactorily, the location of the centre can be taken to be quite reliable. In other cases (i.e.) when the "eye" is not clearly visible, the organization of the cloud bands is poor, clouds are uniformly bright or the picture quality is poor, the location of the centre becomes subjective. Moreover, gridding errors (particularly in pictures where landmarks are not visible) introduce another uncertainty. Finally, we have to reckon with the subjectivity of the analyst. Location of the centre is more accurate for intense systems which are better organised, than in weaker disturbances. The stronger the disturbances, the more accurate the positioning of the centre. The most accurate fixes are for storms with visible "eyes". Taking all these into account, the centre fixes may be taken to be accurate only within half a degree in well-defined satellite pictures, and within a degree or a degree and a half in other cases. On some occasions larger errors have been noticed. A number of studies have been made to determine the accuracy of the positioning using satellite pictures. A very recent summary for 1971 for the West Pacific is given below:

TABLE - IX

Positioning errors (in nautical miles) using satellite fixes*

| Stage | B | C | C+ | X |
|---|---|---|---|---|
| Cases | 21 | 31 | 20 | 97 |
| Mean | 85 | 52 | 30 | 24 |
| Median | 66 | 34 | 27 | 23 |
| R.M.S. | 100 | 71 | 34 | 29 |

*From Annual Typhoon Report 1971, FWC/JTWC, Guam (Table 2-6)

10.7 Intensity determination

10.7.1 The intensity determination is based on the recognition of the 'eye' in the picture, the degree of organization of the bandings and the size of central overcast. The last two factors introduce some subjectivity in picture interpretation. In spite of all these limitations, experienced analysts usually do not differ in categorization of the disturbance, provided the quality of the picture is good. The nomogram used to derive the maximum winds has a scatter of about ± 15 kts. In this connection, a reference may also be made to Appendix V.

10.7.2 Studies of the use of satellite photographs in tropical cyclonic storms have indicated that in the absence of a sufficient number of ship reports within 2 degrees of the estimated centre of the storm, the intensity assigned to the storm in operational work may be weighted towards satellite information, and the difference between the intensities determined from satellite pictures and other conventional methods may not be kept more than one stage of the satellite categorization.

10.8 These points should be borne in mind while using satellite picture information of tropical disturbances in operational work.

10.9 An analysis of the frequency distribution of the satellite-observed disturbances of various intensities in the Indian Seas (Arabian Sea and Bay of Bengal) and the size of the overcast associated with cyclonic storms (i.e. X stage disturbances) is given below (Table X). The analysis is based on NESC bulletins received from Washington and refers to the post-monsoon season of 1968-72.

TABLE - X

a) Frequency distribution of various types of disturbances

| Sea areas | Type of disturbances | | | | | | | | Total No. of Obsns. |
|---|---|---|---|---|---|---|---|---|---|
| | B | C | C- | C+ | Cat.1 | Cat.2 | Cat.3 | Cat. 4 | |
| Arabian Sea | 13 | 4 | 1 | 4 | 0 | 1 | 5 | 0 | 28 |
| Bay of Bengal | 17 | 16 | 1 | 9 | 1 | 11 | 7 | 1 | 63 |

b) Frequency distribution of size of overcast

(size in degrees of Lat./Long.)

| | 2-3 | 3.1 - 4.0 | 4.1 - 5.0 | 5.1 or more | Total No. of observations |
|---|---|---|---|---|---|
| Arabian Sea | 6 | 0 | 0 | 0 | 6 |
| Bay of Bengal | 12 | 5 | 2 | 0 | 19 |

10.10 These figures* are in general agreement with the statistics of tropical depressions and storms given earlier. In the storm type disturbances, categories 2 and 3 are most common and the most common size of the overcast is 2 to 3 degrees. There has been no storm with an overcast diameter less than 2° or greater than 5°. According to this table, during the five year period 1968-72, moderate storms of winds about 55-75 knots cover practically the entire list of storms in Indian seas. Storms of higher intensity are only a few in number.

* In view of the small number of samples, the conclusions in this paragraph may be treated as only tentative.

## 11. Disastrous Weather Caused by Cyclonic Storms

11.1 The destruction caused by cyclonic storms over the coastal areas are produced by

i) Hurricane winds

ii) Torrential rains and

iii) Storm Surges.

### 11.2 Hurricane winds

11.2.1 The fiercest winds associated with a cyclonic storm are packed in a tight ring in the wall-cloud region around the 'eye' in a fully developed tropical cyclone. The hurricane winds may extend over an area of 50–150 km in diameter, while winds exceeding BF8 may extend upto 250 km from the centre. As has been pointed out in the analysis of maximum winds and lowest pressures associated with tropical cyclones in the Indian area, the wind speeds in most storms in the Indian seas do not exceed 90 knots; however, there are a few cases of severe storms where the speeds have reached 100–120 knots. In operational work, satellite pictures are very useful by providing an estimate of the strength of winds associated with the tropical storm, for issuing warnings to coastal belts.

### 11.3 Torrential rains

11.3.1 Very heavy rains occur over coastal areas in association with storms; the heaviest falls are when the cyclonic storm crosses coast. In a general way, it may be stated that the amounts of rainfall will be higher, the more intense the storm. The asymmetrical distribution of heavy rainfall associated with storms crossing the east coast during the post-monsoon season has been discussed in detail in FMU Report on 'Northeast Monsoon'.(FMU Rep. No. IV-18.4).

11.3.2 The analysis of 30 years data of very heavy rainfall associated with depressions and storms during the post-monsoon season shows:

i) Rainfall upto 40 cm has occurred, though amounts as high as 50–55 cm have also been reported very occasionally.

ii) Rainfall of the order of 35–40 cm in the case of severe storms and 20–30 cm in the case of cyclonic storms has occurred on 50% of occasions; on 70% of the occasions of depressions, the amounts have ranged between 10 and 30 cm.

iii) Irrespective of the intensity of the system, there are more chances of very heavy rainfall in October than in November.

## 11.4 Storm surges

11.4.1 The term 'storm surge' is applied to the rise in the sea level associated with a cyclonic storm crossing the coast. Storm surge is responsible for the major part of loss of human life and property caused by cyclonic storms. It has been estimated that 90% of the lives lost in a tropical cyclone is due to drowning in storm surges and floods. In addition to the strength of winds, storm surge depends on many other factors such as the configuration of the coast, the topography of the sea bottom etc. Certain areas such as the coast line around north Bay, south Tamil Nadu coast, Kutch and Cambay etc. are more prone to high storm surges than some other parts of the Indian coast line. When the astronomical tide and the storm surge are in phase, the disaster may be more than when they are in opposition. Hence 'Tide tables' are to be consulted while formulating warnings for tidal waves affecting the coastal regions.

11.4.2 In recent times, methods have been developed to predict numerically the height to which the tidal waves will rise and other details in association with a cyclonic storm. The problem of 'storm surges' and how to predict them will be dealt with in a separate report in the Forecasting Manual series.

11.4.3 A nomogram has been prepared for predicting the maximum surge at the time of crossing coast in respect of north Bay. This nomogram along with equation to calculate the surge heights is given in Appendix VI.

## 12. Low Pressure Areas

12.1 Storms and depressions develop out of low pressure areas. They (i.e. storms and depressions) also weaken into low pressure areas after crossing coast. However, there are cases when low pressure areas which form over the sea areas, move without developing further. On an average, during October and November there may be 2 such low pressure areas over the Indian seas in a month which do not develop further and in many years even 3. In December, they are slightly less – only 1 or 2.

12.2 While some low pressure areas in the Bay of Bengal may be traced from across the Andaman Sea, they often form in situ, in west central Bay and southwest Bay.

12.3 Low pressure areas are delineated on the surface chart by a single closed isobar at 2 mb interval. At times, the closed isobar may only be an 'odd value' isobar. When the area covered by the closed isobar is not wide and diffuse and the associated upper air circulation as far as could be judged from the coastal winds is also well-defined, the system is called a 'well-marked' low pressure area. When the satellite picture shows a heavy mass of clouding associated with the low, which can be categorized as Stage B, the system is always a well-marked low pressure area; at times it may be even a depression. About 40% of the low pressure areas are well-marked. When the closed isobar covers a wide area in the south and the adjoining central Bay of Bengal, and the circulation is also seen in the lower troposphere, it is common practice to describe the situation only as "the seasonal low being well-marked". The seasonal low usually becomes well-marked as a prelude to the formation of a low or a depression.

12.4 In October, we can delineate the low pressure areas even over the sea area unambiguously as they usually form at a slightly northerly latitude and a few observations over Sri Lanka and the south Bay indicate a westerly wind. But later in the season, when the seasonal trough shifts to extreme south Bay, the central region of the low pressure systems may be to the south of 8°N or even further south. Under such circumstances, we may not be able to draw any closed isobar in our chart, which is mainly due to the non-availability of observations in the equatorial region. In such cases, a trough may extend from the low northwards to off Tamil Nadu coast and may appear to be more prominent on our charts than the main low to the south which again is mainly on account of lack of observations in the south to define the low. However, satellite picture may help the analyst on such occasions to delineate the low in the south.

12.5 Figures 12.1(a) to 12.1(c) give the spatial distribution of centres of low pressure areas, monthwise, in the post-monsoon season. The centres have been taken as the geometric centres of the closed isobar defining the low pressure areas. The low pressure areas are seen in the south Bay, Comorin and Laccadives area in October and November. Their higher frequency in Laccadives area is noteworthy. By December they are seen mainly to the east and south of Sri Lanka and in Maldives area.

12.6 It is also noticed that whenever a well-marked system approaches Tamil Nadu coast from the east, it induces a low pressure area in the Laccadives region.

12.7 On an average, there are about 30 days in each year during the post-monsoon season with a low pressure area on the chart in the south Bay, south Peninsula or south Arabian Sea. The number of days are considerably more in October and November than in December. Very often, particularly during the earlier part of the season, two low pressure areas embedded in the trough may be seen simultaneously, one in the south Bay and the other in the south Arabian Sea.

12.8 The upper air cyclonic circulation associated with a low pressure area generally does not extend beyond 850 mb. A large number of them is not seen even at 850 mb. However, when the system is well-marked, the circulation invariably extends to 850 mb or even higher, about 25%-30% of them extending above 850 mb.

12.9 60% to 70% of the low pressure areas (including well-marked systems) do not have any noticeable tilt with height. The rest of them have a tilt usually towards a direction between south and west.

12.10 In a number of cases, the low pressure areas do not show any sequential movement. On a little over 50% of the occasions, they seem to be stationary or weaken in situ. Others move in a westerly direction (between westsouthwest to northwest). A good number of low pressure areas weaken when they approach Tamil Nadu and Sri Lanka coasts. Of the remaining, many show a tendency to move towards a westsouthwesterly/southwesterly direction when they come close to the coast. It may be incidentally observed even in the case a few storms and depressions in this season, a westsouthwesterly to southwesterly movement has been observed as they approach the Tamil Nadu coast. It is not clear whether the Peninsular land mass lying across the path of the low influences the direction of its movement. The number of low pressure areas that cross the Peninsula or Sri Lanka into the Arabian Sea are only a few. They are usually the well-marked ones or the remnants of depressions/storms. In contrast to the Bay, many of the low pressure areas in Laccadive-Maldive area have a movement towards a northwesterly direction.

12.11 The seasonal trough across south Bay, south Peninsula and south Arabian Sea seen on the isobaric charts in the post-monsoon months extends upto 700 mb. Higher up, a broad easterly current prevails which increases in speed with height. As the seasonal trough shifts to the south of Lat. 8°N or so during the second half of the season and also gradually becomes less marked, a nearly zonal easterly flow prevails over south Bay, south Peninsula and south Arabian Sea through a fairly deep layer. In this zonal flow, wave like perturbations may form and move from east to west.

12.12 The main difference between a low pressure area and a low pressure wave is, that in the low pressure area there is a complete cyclonic circulation with west winds in the south, while a wave is a sinusoidal perturbation without any west winds in the south. The low pressure area is embedded in the seasonal east-west oriented trough, while the wave is a perturbation in the deep zonal current.

With these differences, it should, therefore, be possible to clearly differentiate between a low pressure area and a low pressure wave and use the appropriate terminology.

12.13 Even during the earlier part of the post-monsoon season as the upper air pattern above 700 mb is a deep zonal flow, wave motion is possible in the mid- and upper tropospheric easterlies. Such waves may be expected to be associated with low pressure areas in the surface chart and in the lower troposphere, (i.e.) a surface and lower tropospheric low paessure area may extend as a wave trough in the mid-tropospheric levels.

## 13. Seasonal Trough of Low Pressure over the Indian Sea Areas

13.1 The seasonal trough (in surface and upper air) passes from south Arabian Sea to Andaman Sea across the south Peninsula during the month of October. By November, the trough line shifts to the south of Lat. 10°N. By December, the trough shifts still further south.

13.2 The seasonal trough extends from the surface upto about 600 mb on the mean charts, with a southward slope with height, the average slope being about 1/100. The slope of the trough line can be seen clearly in October when the trough is near about 13°N in the surface and there are enough upper air observations to the south of the trough. However, later in the season when the trough shifts southwards, the slope cannot be fixed as there are hardly any upper air observations to the south of trough line.

13.3 The east-west trough becomes well-marked when low pressure areas and depressions form in the south Bay and southeast Arabian Sea. This east-west trough is occasionally seen on the synoptic chart, extending from south Arabian Sea in the west to as far east as southwest Pacific across the south Indian Peninsula and south Bay; and we notice a series of low pressure systems embedded in the trough, spaced at nearly equal intervals (for instance see Figs. 15.1 and 16.3).

13.4 The normal weather over the sea areas is a few sporadio showers or thunderstorms. However, when the seasonal trough becomes well-marked, the thunderstorm activity will increase; but still it may be only scattered. But when a low pressure area or depression forms, there may be areas of heavy convective activity, with increasing squalliness.

## 14. Discussion of Typical Synoptic Situations - General

14.1 The three important types of synoptic situations in the Indian sea areas during the post-monsoon season are:-

i) cyclonic storms and depressions

ii) low pressure areas, and

iii) well-marked seasonal trough of low pressure.

Of these, cyclonic storms and depressions are the more intense systems. Their formation is usually preceded by the seasonal trough over the sea areas becoming well-marked and by the development of low pressure areas embedded in the trough. In many cases, the low pressure areas may not develop further into depressions or storms.

14.2 In the following sections, we will discuss a few typical synoptic situations of cyclonic storms. As the other synoptic situations (i.e.) well-marked seasonal monsoon trough, low pressure area and depression are included in the discussion of the storms, as antecedent synoptic features, separate discussions of these weather systems have not been attempted.

14.3 In a manual of this type, it is felt that case-histories discussed should be fairly well-documented by data. Consequently, only such instances have been selected in which there was a good coverage of data - particularly ships' observations. But very often, in practice, forecasters have to work under the severe handicap of data limitation; in some cases there may be practically no other data in the storm field except a satellite picture.

## 15. Severe Cyclonic Storm in the Bay of Bengal – – 3 to 8 November 1969

15.1 This storm developed out of a low pressure area which moved into the Andaman Sea from the Gulf of Siam across Tennasserim. The low pressure area reached the Andaman Sea by 3rd November 1969 (Fig. 15.1). Another low pressure system had moved earlier across the Andaman Sea from east to west. Even a week before this date, the east–west oriented seasonal trough was well–marked extending from southeast Arabian Sea to southwest Pacific across south Bay of Bengal and was persisting. A number of low pressure areas were embedded in the trough, some of them moving from east to west; a few of them developed into storms – two in the Pacific and one in the Bay of Bengal.

15.2 On the 3rd morning, the pressure departure associated with the low pressure area was about –4 mb, in a field of a general negative departure of 1–2 mb over most of India, Bay of Bengal and Burma. The continued pressure fall over the area and the persisting widespread rainfall and heavy clouding on this day were indicative of futther development (Fig. 15.2).

15.3 By 4th morning the low pressure area concentrated into a depression, with its centre about 100 km northeast of Port Blair (Fig. 15.3). The intensification into a depression was indicated by

i) the two closed isobars over the Andaman Sea and the Bay Islands

ii) a pressure departure of about –5 mb over the Bay Islands which was concentrated over a relatively small area and was not part of a wide field of negative departures (this was in contrast to the pressure departure field on 3rd) and

iii) the satellite showing a stage C+ pattern. In the lower tropospheric wind field, Port Blair winds were still light to moderate (hardly reaching 10 knots) at levels below 2.1 km, while winds along Burma coast were considerably stronger reaching upto 30 knots (Fig. 15.4). This feature of weaker winds near the centre and considerably stronger winds at large distances away is a characteristic of the developing stage of tropical disturbances.

The circulation, however, extended upto 500 mb.

15.4 The depression deepened during the course of the day (4th)(Fig. 15.5). The central pressure of the system, which was nearly constant till 4th morning, showed a relatively rapid fall during the course of the day. Compared to 0300Z when the central pressure of the system was 1006 mb, the central pressure in the evening became about 1001 mb and there were at least 3 (if not 4) closed isobars at 2 mb intervals. The 24 hrs. pressure changes were also about 3–4 mb (negative) and concentrated over the north Bay Islands and the lowest departure was –8 mb. (Note the concentration of negative departures on this day over the Bay Islands and compare it with 3rd morning pressure departure field).

15.5 The deep depression moved westnorthwestwards and further intensified into a cyclonic storm by 5th morning with its centre within half a degree of 13°N 90°E (Fig. 15.6). The indications of the cyclonic storm stage were:

i) The satellite picture (Nimbus 3) showed an intensity of Stage X Cat.2, with the diameter of the central overcast about 2°. This gave a maximum wind of about 55 knots.

ii) The surface winds of north Bay Islands group of stations increased considerably in speed since 4th evening, reaching 20/30 knots, although the system was moving away westwards.

iii) The winds reported by ships at 400–500 km away from the centre were as much as 25 knot strong in the west and 40/50 knot in the north.

iv) The lower and mid-tropospheric upper winds at Port Blair (06Z and 12Z) (Fig. 15.7) strengthened considerably and were 30/40 knots although the system was moving away from the station and there was no appreciable change either in the speed or in the direction of these winds upto 300 mb.

15.6 All these gave a conclusive evidence that the system had reached storm stage. It is interesting to note that while the Bombay APT analyst classified the ESSA 8 (0918 IST) and Nimbus 3(1016 IST) pictures of the disturbance as

Stage X Cat. 2, the Washington analyst classified the ESSA 9 (1313 IST) picture of the disturbance as C+ only. This brings out the close similarities between C+ and Stage X Cat. 2.disturbances, and to a certain extent the subjectivity introduced by the analyst in distinguishing the two types. In this particular case, we had ships reports at the periphery of the circulation which also gave a centre fairly agreeing with the satellite-determined centre. It may be pointed out that the lower tropospheric winds all along the east coast and over Sri Lanka were north/northeasterly. It was, therefore, quite difficult to use these winds to determine the centre of the storm. The Port Blair winds (06Z), however, gave a reasonable fix of the storm centre. The strengthening of the northeasterlies along Orissa and north Andhra coasts with the disturbance so far away is another interesting feature.

15.7 Although the pressure changes (on 5th morning) over the east and south Peninsula were negative, they were positive along the Arakan coast. The storm was too far away from the coast to reach any definite conclusion regarding the movement of the storm from these pressure changes. The 24 hour pressure change chart in the evening (of 5th) showed general rise of pressure all over India, Burma and the Bay Islands with a fall over West Central Bay and the adjoining east coast of the Peninsula. This was an evidence of the further strengthening of the storm.

15.8 The storm centre was 5° or more to the south of the sub-tropical ridge line at 200-150 mb on the 5th and the upper tropospheric flow pattern suggested a westnorthwesterly movement for the storm. Extrapolation of past 24 hours track also gave westnorthwesterly movement only. However, climatological direction had a slight bias towards north. In view of the absence of any trough in the upper westerlies as well as the sub-tropical ridge position on this day, any northward movement was discounted.

15.9 On the 6th morning the storm was centred near 14.5°N 87°E and the satellite pictures (ESSA 8 and Nimbus 3) showed an 'eye' for the storm (Fig.15.8). The immediate inference from the satellite picture was that the storm had further intensified during the preceding 24 hrs and had become severe (an indication of the same was provided by the 24 hour pressure changes on 5th evening as discussed earlier in para 15.7). The Bombay APT station classified the disturbances Stage X Cat.3 with a diameter of 4 to 5 degrees; from which the maximum wind speed can be put as about 80–90 knots. It may, therefore, be inferred that winds in the storm field had hurricane strength. There was no ship observation in the storm field except at the periphery. In such cases the forecaster has to depend heavily on satellite data for fixing the centre of the storm as well as its intensity. The nearest observations were, on this day 3–4 degrees away from the storm centre and reported winds of speed 30/40 knots. These strong winds so far away from the centre were consistent with the system being a severe cyclonic storm with a core of hurricane winds.

15.10 Compared to the previous day (5th), the 24 hour pressure changes along the east coast of the Peninsula were significant as the storm moved northwestwards towards the coast. A fall of about 4 mb was noticed over north Coastal Andhra Pradesh. The pressure departure over the same area was also about –4 mb. The pressure change and departure charts indicated that the severe storm may move towards north Coastal Andhra Pradesh.

15.11 The storm position was also well to the south of the ridge line at 200 and 150 mb (Fig. 15.9), and a westnorthwesterly movement of the storm was also consistent with the wind flow at these levels. Climatology was not quite useful on this day also to forecast the track.

15.12 In view of

i) pressure changes

ii) strengthening of lower tropospheric winds along north Coastal Andhra Pradesh

iii) 200 mb wind pattern and

(iv) previous 24 hrs track, a continued westnorthwesterly movement was indicated. By 6th evening the winds in the lower troposphere along north Andhra Pradesh and south Orissa coasts further strengthened as the severe cyclonic storm moved closer to the coast (Fig. 15.10). The winds along the east coast had also come within the grip of the circulation (compare 6th 12Z chart with 5th 00Z and 12Z* and 6th 00Z upper air charts).

15.13 On the morning of 7th there were enough ships observations in the storm field to fix the centre as well as to determine the intensity. A ship reported wind speed of 80 knots and a pressure of 987 mb (Fig. 15.11). The satellite reported "eye visible". The Ci outflow and the 'bandings' were characteristic of a severe system. The storm had increased in size since the previous day and it was categorized on 7th morning as Stage X Cat. 3 with a diameter of 6 to 7 degrees, which gave a maximum wind of about 90 knots to 100 knots. The diameter of the overcast had increased since the previous observation.

15.14 All the observations (ship's, upper air and satellite) suggested that the system was one of severe intensity with a core of hurricane winds and it was centred near 16°N 84°E on the morning of 7th.

15.15 The 24 hour pressure changes showed 8-9 mb fall along the north Andhra coast and the maximum fall was at Kakinada - which reported a pressure of 996.1 mb, the lowest along the coast. The pressure departure was -17 mb at Kakinada. Though Vizag and Kakinada reported strong surface winds ranging from 25 to 40 knots, their directions did not indicate the bearing of the storm centre uniquely. Surface winds reported by coastal stations are vitiated by local topography and exposure conditions. Generally their speeds are an under-estimate of the intensity of the system out at sea. Similarly, the direction also will have to be judiciously used for fixing the centre of storm. The pressure changes and departures showed a west-northwest/northwest track and it could be expected to hit the coast near about

* Not reproduced.

Kakinada where the pressure fall was maximum.

15.16 At 200–150 mb, the storm continued to be well south of the ridge line (Fig. 15.12). The upper tropospheric ridge line, climatology and persistence were also in favour of the continued westnorthwest/northwesterly track; the pressure change distribution along the coast line gave further indication as to the location where the storm was likely to strike. Hourly observations from the coastal stations – (when the storm is at such close distances as on 7th morning) – will be helpful in narrowing down the coastal strip where the storm may be expected to strike. Hourly radar reports together with these hourly surface observations may enable the forecaster to locate with a high degree of confidence the place where the storm may be expected to strike the coast.

15.17 The storm crossed the coast just south of Kakinada and was centred at 1730 hrs close to Nidadavole (to the south of the station) (Fig. 15.13). Nidadavole (16°55'N, 81°40'E) reported a pressure of 975 mb at 1730 hrs of 7th which was 36 mb below normal. This was the lowest recorded pressure in the coastal area in the path of the storm and the maximum wind reported was about 150 kmph (81 knots). At Kakinada it was 107 mph (93 knots). Since the storm crossed the coast near about the time of low tide, the tidal waves did not rise very high. The height was only about 8 to 10 feet and sea water entered inland upto a maximum distance of 5 to 6 miles only.

15.18 Moving across Telangana, the severe cyclonic storm weakened and lay as a cyclonic storm centred near Hyderabad on 8th morning (Fig.15.14). The upper tropospheric winds showed that even after crossing coast and weakening, the cyclonic storm extended upto 200 mb, it was about 4° in diameter at this level (Fig. 15.15). During the 24 hour period ending at 0830 hrs of 8th, heavy to very heavy rains occurred in north Coastal Andhra Pradesh in association with the storm crossing the coast. Rainfall of the order of 15 cm was recorded at a number of state raingauge stations, the highest amount being 19 cm at Bhimavaram in West Godavari district.

15.19 During the subsequent 24 hours, the cylonic storm weakened into a depression and moved towards north Madhya Maharashtra where it weakened further.

15.20 The structure of the wind field associated with the storm has been prepared compositing the ships'observations for a period between 6th 0000Z and and 7th 1200Z ~~during which period~~ when the storm was severe with a core of hurricane winds (Fig. 15.16). Some of the interesting features brought out by the composite are:-

i) winds exceeding 50 knots are confined to within 100 km of the centre*

ii) Outside this small area of 100 km radius, there is considerable asymmetry in the wind field. Strong winds of speed 35/40 knots (lower limit of storm strength) extends very much further in the northern quadrants (right quadrants) than in the southern quadrants. The rate at which the wind speed falls off from the centre is a maximum in the southwest quadrant.

iii) The cyclonic circulation covers an area of about 8 degrees radius

iv) there are some bands of strong winds in the ~~southeast and~~ eastern quadrants; they seem to agree with the major cloud bands feeding into the main central overcast.

v) the overcast cloud area is generally bounded by the 20 kt isotach.

vi) considerable inflow into the storm is indicated by the observations close to the centre.

15.21 An interesting feature of upper tropospheric flow during the period was a temporary strengthening of the easterlies. They reached 50 knots and more over Trivandrum, Colombo and Madras between 6th evening and 8th morning.

## 16. Severe Cyclonic Storm Recurving over the Bay – 2 to 6 November, 1971

16.1 During the second half of October, 1971 and in the beginning of November, the seasonal trough was extending from south Arabian Sea to southwest Pacific across south Bay of Bengal and Gulf of Siam. It was well-marked on most of the days during the period and a number of low pressure systems were embedded in the

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* If we consider the 0.9 km upper winds reported by coastal stations, there is probably another wind maximum of the order of 50 kts to the northwest of the storm centre.

trough (for instance, see Fig. 16.3). A few of them (one in the Arabian Sea, two in the Bay and two in the southwest Pacific) developed into tropical cyclones between the second half of October and the first half of November. In addition, there were a few depressions in the southwest Pacific and the south China Sea. In this section, we will discuss one of the cyclonic storms in the Bay, which developed in south Andaman Sea, recurved over the Central Bay and hit Bangla Desh coast.

16.2 The system initially developed as a low pressure area in the south Andaman Sea on 2 November and it was embedded in the seasonal trough (Fig. 16.1). Although there was only one closed isobar on the surface chart, the circulation extended upto the mid-troposphere (Fig. 16.2). There is some evidence to show that the low pressure area moved into Andaman sea from the east.

16.3 During the next 24 hrs. the low pressure area moved westwards and became well-marked. It lay on 3rd morning over the south Bay Islands, where the 24 hour pressure falls were about 2 to 3 mb and the maximum departure was -2 mb (Figs. 16.3 and 16.4). The winds over Port Blair strengthened during the previous 24 hrs. and also veered. They reached 20/25 knots in the lower and middle troposphere (Fig. 16.5). There was also considerable rainfall in the Bay Islands; rainfall was of the order 3-6 cm and was accompanied by thunder. The satellite pictures also showed a heavy overcast blob of cloud (stage 'B') about 8-10 degrees in diameter over the area, with its geometric centre near 11.5°N 95°E, and bright convective area in south and west quadrants. All these features indicated that the system may develop further. The well-marked low pressure area became a depression by the same evening.

16.4 By the 4th morning, the depression moved northwest and was centred near 12.5°N 91°E and it was deep (Figs. 16.6 and 16.7). The deepening of the depression was indicated by the following:-

i) two closed isobars at 2 mb intervals.

ii) pressure falls of 3–4 mb and pressure departure of –3 to –4 mb over the north Bay Islands, despite the fact that the depression was about 1–2 degrees to the west and

iii) satellite picture reporting Stage C+, compared to Stage 'B' on the previous day.

16.5 Although the depression was moving northwestwards, away from Port Blair, the lower tropospheric winds at Port Blair veered further and strengthened to 25 knots by 1200Z, without changing much with height upto nearly 300 mb. This suggested a further intensification of the system into a cyclonic storm stage.

16.6 By 5th morning the cyclonic storm was centred near 16°N 89°E (Fig.16.8). There were no ships observations close enough to the centre; hence the satellite information was the main basis to judge the intensity of the storm. The bearing of the storm centre from the perepheral ships' data and satellite pictures centre differed by about 1.5 to 2 degrees of latitude. As the available ships' data did not suggest such a high latitude for the centre as given by the satellite, the centre was fixed at a more southerly latitude consistent with the ship observations. The satellite picture gave the system as Stage X Cat. 2 and diameter 4, which corresponds a maximum wind of about 60 knots (about 10 knots above the lower limit for a severe cyclonic storm). Probably the system was on the border line of a severe storm.

16.7 There was a general fall of pressure of about 1 mb over the whole of India and north Burma; but the changes along north Andhra, Orissa and West Bengal coasts were relatively more (about 2.5 mb). The climatological track in this area had a northeast bias; extrapolation of the past track would give a northwest/northnorthwest movement. But in the upper air, the flow pattern gave some conclusive indications. A deep westerly trough extended on this day from Western Tibet to north Coastal Andhra Pradesh and adjoining west Central Bay as far south as 15°N in the mid-and upper troposphere (Fig. 16.9). It was progressing eastwards across the country during the previous 2-3 days (see Figs. 16.2, 16.5 and 16.7). The location of the cyclonic storm ahead of the progressive trough is a typical situation for recurvature. The position of the cyclonic storm was also close to the subtropical ridge line at 200-150 mb. Thus, though the pressure changes and extrapolation of the past track suggested a northwesterly track, the westerly trough system was quite prominent and was the dominant feature.

16.8 ESSA 9 afternoon (0907 GMT) bulletin and the aircraft reconnaissance reports (1230Z and 1430Z) confirmed that the storm was a severe one and that it had also changed its course to north/northnortheast since the morning. The satellite categorization, Stage X Cat. 2 Diameter 6, gave a maximum wind of about 70 knots which was agreeing quite well with the aircraft reporting at 700 mb a wind of 70/75 knots.

16.9 By this time (5th 1200Z) the well-marked westerly trough had moved slightly eastwards. Since the storm had already changed its course to a northnortheasterly direction, further northnortheast/northeast movement was the logical forecast. 24 hour pressure changes at 1200Z over Assam and Bangla Desh were 1-2 mb positive, while over Orissa, West Bengal coast pressures fell by 2-3 mb. The pressure change of -4 mb at Akyab was the highest on the chart, which was more than the pressure fall along West Bengal and Orissa coasts at comparable distances from the storm centre (see inset in Fig. 16.8). Thus the factors in favour of a northnortheast/northeasterly movement were more weighty than a movement in any other direction. The backing of the winds along West Bengal coast during the night was consistent with a movement of the storm towards Bangla Desh.

16.10 The severe cyclonic storm moved northeastwards and was close to Cox's Bazar-Chittagong coast by 6th morning (Fig. 16.10). Except for Chittagong, there were no observations from Bangla Desh. Aircraft reconnaissance gave the centre at 0230Z near 21.4°N and 91.4°E "with a circular eye of diameter 25 miles and surface winds of 70 knots strength". Satellite picture (about one hour later) reported the centre near 22°N 92°E and Stage X Cat. 2 and Diameter 4 degrees. But, the 'eye' was not visible in the satellite picture. Surface observations around northeast Bay were scanty. The crucial observation was from Chittagong which reported northeasterly 30 knots and a pressure of 991.2 mb which was nearly 23 mb below normal. Taking all the data into account, the centre could be fixed near 22°N 91.5°E on 6th morning. We had in this case three types of data – aircraft reconnaissance, satellite and coastal observations (though they were scanty), all of them at nearly the same time. This affords a good instance of inter-comparison among the different types of observations.

16.11 24 hour pressure changes, upper air flow pattern, persistence as well as climatology were all in favour of a continued northeastward movement. The severe storm crossed coast by 06Z near Chittagong where the lower tropospheric winds (upto 0.9 km) changed to westerly 50 knots (Fig. 16.11).

16.12 The storm developed from a low pressure area in the seasonal trough. The sea surface temperature over the area where the storm developed was 27°C or more. The scanty ships' observations showed that the sea surface temperature was between 27°C and 29°C over the Bay of Bengal (north of Lat. 10°N). The severe cyclonic storm moved north and subsequently northeast under the influence of an eastward progressing westerly trough in the middle and upper troposphere which extended well to the south – as far as 15°N. This was one of the few storms in the Indian sea areas in which there was aircraft reconnaissance, so that the centre and the intensity could be accurately fixed. In view of the paucity of ships' data, the analyst had to lean heavily on satellite pictures and the aircraft reconnaissance. As the storm was fairly far away from the Indian coast (except in the last stages when it moved into northeast Bay) the pressure changes and departures from coastal areas did not give any usable information regarding intensity or location of the centre.

## 17. Severe Cyclonic Storm in the Arabian Sea – 5 to 12 November 1966

17.1 In this section we will discuss the case of a severe cyclonic storm in the Arabian Sea. Storms and depressions form in the Arabian Sea either in situ or under the influence of low pressure systems from the Bay of Bengal travelling westwards across the south Peninsula. Statistics for the past years indicate that in the case of 50% of the depressions and storms in the Arabian Sea, the origin could be traced back to the Bay. In the case to be discussed in this section, a depression moved westwards across the south Peninsula into the Arabian Sea. This case has also been chosen to illustrate the methods of analysis and prognosis to be adopted while dealing with storms over large data-void areas.

17.2 A severe cyclonic storm which struck the Tamil Nadu coast on 3 November, 1966, weakened into a depression and moving across the south Peninsula emerged into the Laccadives area during the night of 4th. On the morning of 5th it was centred about 150 km east of Amini Divi (Fig. 17.1). There were two (and probably three) closed isobars around the centre and the pressure departure at the centre was about –7 mb. The circulation extended upto 500 mb level (Fig. 17.2).

17.3 Climatology and past 24 hours track indicated a future movement between west and northwest. The easterlies over Trivandrum in the upper troposphere were also favourable for a west/northwest movement. Due to lack of data, pressure tendencies out at sea could not be judged. The depression moved due west and was centred to the west of Amini Divi by the evening.

17.4 On the morning of 6th, the depression was centred about 150 km west of Amini Divi (Fig. 17.3). The centre could be inferred by the upper winds over Arabian Sea Islands and Kerala–Mysore coasts which were still under the grip of the depression (Fig. 17.4). In the satellite picture, the geometric centre of the cloud mass was near about 12°N 70°E.

17.5 In view of the lack of surface and upper wind observations from the Arabian Sea, climatology and persistence became the only tools available for the prediction of the movement, from 6th onwards, On their basis, a continued west/northwesterly movement could be forecast on the 6th. Although there were no ships observations in the immediate neighbourhood of the depression, the perepheral ship reports gave a sea surface temperature ~~ragging~~ ranging from 28°C to 29°C (the mean monthly sea surface temperature over the area is about 28°C). Even though there were no surface or upper air data, in view of the favourable sea surface temperature conditions and the anticipated movement of the depression towards an area which is climatologically favourable for intensification into a cyclonic storm, it could be forecast that the depression might intensify.

17.6 The depression moved in an almost westerly direction and was centred on 7th morning near 11.5°N 68°E (Fig. 17.5). It had also intensified into a cyclonic storm as anticipated. There was no observation within 3 to 4 degree of lat./long. of the storm centre, although there was a good scatter of data (ships and island stations) at the periphery of the storm circulation. These observations (at 5 to 7 degrees away) reported winds of speed 15/20 knots well under the grip of the circulation. This was one indication of the intensification of the system (compare with the 6th morning wind circulation). Bearings from these ships from such large distances gave the centre of the storm which was probably correct only within a degree or so. The satellite pictures also showed that the system had intensified, though no 'eye' had yet appeared and gave a centre which was in fair agreement with the one determined by the peripheral ships' observations. The satellite picture for the day (Nimbus 2–0712 GMT) suggested that the storm had reached severe intensity. This was supported by 12Z ships reporting 30 knots at a distance of about 2° from the centre. Ships also reported sea surface temperature of 28°C to 29°C over the storm area, suggesting that the storm might intensify still further. Climatology suggested a more northerly component of motion on this day.

17.7 Again on the 8th, while the peripheral ships' data were plentiful, none of them were within 3° of the centre (Fig. 17.6). The circulation associated with the storm was fairly extensive, of the order of about 12°–14° of lat./long. diameter. By the afternoon, the satellite picture (ESSA 3 – 1034Z)* reported 'an eye' at 12.5°N 65.5°E and a diameter of 7° lat./long. for the central overcast. Since an eye has been reported, we may take the centre fix from the satellite to be quite reliable. Maximum winds as derived from the satellite picture was nearly 100 knots. The storm had, therefore, become severe with a core of hurricane winds.

17.8 On the 9th, even the peripheral ships' observations became less in number and they were also only from the eastern and southern quadrants (Fig. 17.7). Thus, from the ships' data, the centre and the intensity of the storm could not be satisfactorily determined. However, satellite picture (ESSA-2 APT) at 0456Z showed that the storm was one of severe intensity and its centre was near 13°N 63°E). The picture was too much to the edge. ESSA 3 at 0933Z* reported "visible eye" of the storm "with external and internal bandings". It is interesting to note that ships to the south of the storm at distances of 3 to 5 degrees away reported only 15/20 knot although the storm was a severe one, with maximum winds nearly 100 knots.

17.9 On 10th and 11th two crucial ships' observations were received near the centre of the storm, reporting winds of speed 50–70 knots. This together with the APT pictures enabled the positioning of the storm and determination of its intensity. The severe storm was moving in a westnorthwesterly direction and was centred on 10th near Lat. 15.5°N 61°E (Fig. 17.8) and on 11th near 16.5°N 57°E (Satellite picture in Fig. 17.8).

17.10 The APT pictures showed that the severe storm had been maintaining the same intensity with maximum winds of the order of 100 knots in its circulation.

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* Not reproduced.

Continuing to move westnorthwestwards it crossed Arabia Coast near about 17°N by 12th morning.

17.11 In view of the complete lack of data over the west Arabian Sea and Arabia coast, the forecaster had to depend solely on satellite pictures and stray ships data for positioning and intensity determination and on climatology and persistence for forecasting the movement. Between 9th and 11th when the storm track was between 13°N and 17°N, west of 65°E, climatology suggested even a possible recurvature towards northeast. Over these areas, climatological frequencies are based on very few samples (3-4 in every $2\frac{1}{2}$ degree square for a 70 year period). Thus perhaps persistence is the only factor which the forecaster has to go by in such cases.

17.12 The important points to be noted in this sequence, particularly with reference to methods of analysis and prognosis while dealing with storms in data-void areas, are:-

i) This was a case of a severe cyclonic storm in an area of little or no synoptic data. The only regular data available was the satellite pictures* but they were also at 24 hrs intervals only (ESSA 3 pictures were available at about 0900Z daily, ESSA 2 APT at about 0300 Z and Nimbus APT pictures at about 0700Z). The ships' observations were mostly at the periphery of the storm circulation. Only two observations were fairly close to the centre (one on 10th morning and the other on 11th morning).

ii) After the disturbance moved to the west of the Arabian Sea group of islands, the centering of the storm and the estimation of the intensity had to be based mainly on satellite pictures. Satellite picture information being available only once in a day, extrapolation on the basis of earlier speed of travel was the only consideration to fix the centres at intermediate hours. Night-time I.R. picture will be a very valuable aid to supplement the daytime TV pictures. While using the satellite data on such occasions,

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* In 1966, the present system of categorization of tropical disturbances over sea areas had not come into use.

the forecaster should bear in mind the limitations and the degree of subjectivity in the interpretation of satellite pictures of tropical storms.

iii) The peripheral observations were generally 5 degrees of lat./long. or more away from the centre. In addition to the two ships observations on 10th and 11th referred to above, only one more ship was available within three degrees of centre (at 1200Z on 7th) and it reported 30 knots speed. Analysis of composite wind data in the case of severe cyclonic storm over the Indian sea area by Koteswaram and Gasper (referred to in Sec.4) has shown that in the mean picture also, the speed drops to 30 knot at 3° to $3\frac{1}{2}$° of lat./long. from the centre of a severe cyclonic storm while the central speed is 60 knots. Aircraft reconnaissance in the Pacific and Atlantic have also shown that wind speeds in hurricanes and typhoons generally fall to 30/35 knots or even less, at distances of the order of 3° lat./long. from the centre. Thus, in the case of a cyclonic storm, if wind speeds of 30/35 knots are reported at a distance of about 3 to 4 degrees from the centre, this can be a sufficient basis to classify the system as a severe cyclonic storm with a core of hurricane winds.

iv) In this case, the winds even at 5° to 7° away from the centre were under the grip of the circulation. Thus, from such peripheral winds also we may derive some information about the intensity of the disturbance. However, the bearing of the centre estimated from ships observations at such long distances will be correct within a degree or two only.

v) In such cases where the storm is moving in data-void areas, the forecasting of the movement is also very difficult. Satellite derived upper winds may give some idea of the upper level flow pattern. But the forecaster has to lean primarily on climatology and persistence. In some portions of the sea areas (particularly in the west Arabian Sea), climatological statistics have been based on so few observations that the statistics is not of much utility.

vi) As already seen during the discussion of this storm, the storm intensified while it was travelling over warm waters. The sea surface temperature observations should be useful in indicating intensification or weakening of the disturbances out at sea.

## 18. Severe Cyclonic Storm in the South Bay of Bengal – 17 to 24 December, 1964

18.1 In Sec.15, we have seen a severe cyclonic storm which struck the Andhra Coast. We will now take up the case history of a severe cyclonic storm which struck south Tamil Nadu and Sri Lanka coasts. It crossed Tamil Nadu coast near 10°N, although more commonly cyclonic storms strike coast a little to the north viz. the coastal strip between Nagapattinam and Pondicherry. In some respects this cyclonic storm – commonly known as Rameswaram Cyclone – was peculiar. It formed initially as a depression near Lat. 5°N and later intensified into a severe cyclonic storm at the same latitude. Formation and intensification at these very low latitudes is very rare. In the past nearly 100 years, there has been hardly half-a-dozen such cases. The cyclonic storm formed towards the end of the post-monsoon season. It travelled as a severe storm a fairly large distance over the oceanic area. It was associated with a severe storm surge when sea water rose to 5 to 6 metres and swept away an entire passenger train and hundreds of people in the small islands in the Palk Straits.

18.2 A depression in the south China Sea which was near 7°N 101°E on 14th moved westwards across Malay Peninsula, weakened and reached extreme south Andaman Sea on 16th morning (Fig. 18.1). The relatively larger pressure fall at Nancowry and the increased rainfall (with some heavy amounts) in the south Bay Islands on 16th were significant signs of the arrival of the low pressure area.

18.3 By 17th morning, the low pressure area intensified into a depression with centre near 5°N 93°E (Fig. 18.2). There were 2 (and probably 3) closed isobars around the centre and the maximum negative pressure departure was about 6 mb. Due to complete absence of data, the upper air regime over the depression field could not be known. Rainfall continued widespread over south Bay Islands with isolated heavy falls.

18.4 During the next two days, 18th and 19th, the depression showed only a slight movement westwards (about a degree in 2 days), but it was deepening as could be inferred from the ships observations in the field. By 19th, 4 closed isobars could be drawn around the centre (Fig. 18.3). The winds in the depression field ranged from 15 to 25 knots. The lowest pressure was of the order of 1000–1002 mb, with a departure of about –10 mb at the centre. Thus, the system was in the process of intensification into a cyclonic storm from a deep depression. Pressure changes in the south Bay Islands did not give any indication of the intensification, as the system was still further to the south. But there was a strengthening of the upper winds over Port Blair and Victoria Point below 850 mb (Fig. 18.4). Sea surface temperatures in the field of depression were between 27°C and 29°C, a feature very favourable for development of a cyclonic storm.

18.5 Between 19th evening and 20th morning, the deep depression rapidly intensified into a severe cyclonic storm and was centred near 5°N 91°E on 20th morning.(Fig. 18.5). The intensification could be inferred by a ship which reported a wind of 55 knots within a degree of the centre. But for this observation, it would not have been possible to judge the intensification from the other available ships' observations and there was also no satellite picture over the area in 1964 on an operational basis. In view of the regular availability of the satellite pictures on an operational basis now–a–days, missing a system or failing to judge its intensity due to lack of ships' observations is not likely to occur now.

18.6 Since the storm was far out in the sea, the pressure changes over the mainland or the Bay Islands were not helpful. Extrapolation of past 24–48 hrs. movement of the system gave a nearly westerly track. In the lower and mid–tropospheric levels, the storm was in the field of broad easterlies (Fig. 18.6). The climatological movement over the area showed a northwesterly track but it was based on just a single case and hence could not be relied upon. On the basis of the synoptic data we can predict a westerly movement.

18.7 The severe cyclonic storm moved in a westnorthwesterly direction and was centred near 6°N 88°E on 21st morning (Fig. 18.7). The centre of the storm and its intensity could be judged fairly confidently from the ships' observations. The maximum reported wind velocity was about 60 knots.

18.8 The satellite picture for the day also showed a well-formed eye. The satellite pictures and the actual reports of 60 knots within $\frac{1}{2}$ to $\frac{3}{4}$ of a degree from the centre, led to the inference that the storm had apparently winds of hurricane force in its circulation.

18.9 In response to the westward movement of the severe cyclone, the winds at Port Blair veered (21st morning) (Fig. 18.8), while the winds over Sri Lanka and Tamil Nadu coast backed (21st evening) (Fig. 18.9), and the east coast winds came in the circulation of the cyclonic storm. On this day, at 200 mb and 150 mb levels, the storm centre was south of the sub-tropical ridge line by about 3–4° Lat. By the evening, this feature became more apparent as the ridge shifted further north. On this day also, climatology could not provide any helpful guide because of the very poor number of samples over the area. Past movement as well as the upper flow pattern over the south Bay, indicated only a west/westnorthwest movement.

18.10 Moving in a westnorthwesterly direction, the severe cyclonic storm was centred near 7°N 83.5°E on 22nd morning (Fig.18.10). Ships within $1\frac{1}{2}$ to 2 degrees of the centre reported winds of the order of 45/50 knots, so that winds nearer the centre would have been much stronger and presumably winds of hurricane force continued near the centre.

18.11 With the approach of the storm, pressures showed a fall (for the first time) over Tamil Nadu coast and east Sri Lanka, where Trincomalee reported 2 mb fall. Climatology indicated a westnorthwesterly/northwesterly course. In view of the fairly good number of ships observations in the storm field, pressure changes over the sea area could be worked out. Surface pressure changes for the

15 hour period 21/1200 GMT to 22/0300 GMT gave a maximum pressure fall towards a northwesterly direction (see inset in Fig. 18.10). The upper troposphere (200–100 mb) broadscale flow pattern was also strong southeasterly over the field of the cyclonic storm (Fig. 18.11). All these factors suggested a curving of the track to a northwesterly direction.

18.12 By the evening the severe storm moved northwest and was off northeast coast of Sri Lanka, near 9°N 82°E (Fig. 18.12). Trincomalee reported a northwesterly wind of 25 knots and a pressure 992.5 mb, with a 24 hours pressure change of –8.2 mb and departure of –16.8 mb. The upper winds over Sri Lanka and extreme south Peninsula were well within the grip of the circulation, atleast upto 400 mb level (Fig. 18.13). The 24 hours pressure changes clearly indicated a west to westnorthwesterly track, though climatology and persistence were in favour of a northwesterly track. The storm passed across Sri Lanka just to the north of Trincomalee where the pressure dropped by about 1" and the wind strength reached 100 mph (87 knots) (as given by Ekanayake, 1968).

18.13 By 23rd morning, the severe cyclonic storm was over Gulf of Mannar, with its centre near Mannar (Figs. 18.14 and 18.15). The 'eye' passed over Mannar during the early morning hours of 23rd and the maximum winds at Mannar reached 98 mph (85 knots). The lowest pressure was 978 mb. By the evening it moved into extreme south Tamil Nadu. 24 hour pressure changes, climatology and previous track were all in favour of a continued westnorthwesterly track. The severe storm weakened as it moved inland and emerged as a depression into the Laccadives area by 24th morning.

18.14 The sea surface temperatures in southeast Arabian Sea were generally 27°C and hence favourable for development. But climatologically hardly any development occurs in December in Laccadives area though the area is favourable for development in October and November.

18.15 The depression weakened as it moved away westwards across the Laccadives. With the available synoptic data it is not possible to explain why the system weakened over the Arabian Sea, in spite of the sea surface temperature being quite favourable for development.

18.16 A chart compositing the sea surface temperature observations between 16th and 23rd December has been prepared utilising all available ships data. The isopleths of the sea surface temperature distribution over the Bay south of 15°N west of 100°E, is shown in Fig. 18.16. The track of the storm is also superposed on the analysis. The composite chart shows that the sea surface temperature over the south Bay ranged between 27° and 29°C. There was a belt of slightly higher sea surface temperature of 27.5°C to 29°C over the area between 5°N and 10°N. The development into a storm and its track as a severe storm was almost confined to this area of sea surface temperature greater than 27.5°C. This chart clearly brings out the storm formation and its movement over areas of warm sea surface temperatures.

18.17 A composite wind chart for the period 21 to 22 December 1964 when the storm was of severe intensity is given Fig. 18.17. The chart shows the distribution of winds around the centre, in the field of the storm. The main features brought out by the composite chart are:-

i) Strong winds of 50 knots (lower limit for a severe cyclonic storm) or more did not extend beyond $1-1\frac{1}{2}$ degrees of the centre. This was also noticed in the storm of November 1969 (see Fig. 15.16). Winds of 30 knots speed did not extend beyond 3°.

ii) Although winds reported by the ships were about 50-60 knots only even at distances of about $\frac{1}{2}$ to 1° from the centre, the maximum winds in the wall-cloud region were of the order of 85-90 knots (as recorded at Trincomalee and Mannar during the passage of the storm).

iii) Compared to the November 1969 case, the areal extent of the cyclonic circulation in the present case did not extend beyond 3 to 4 degrees of the centre, though in both cases the maximum winds in the inner core were of the same order.

iv) Stronger winds extended over a larger area in the northern quadrants than in the southern quadrants.

## ACKNOWLEDGEMENT

The authors wish to record their gratitude and thanks to Dr. P.K. Das, Deputy Director General of Observatories (Forecasting), for going through the article and giving many helpful suggestions.

## APPENDIX – 1

(Extracts from the Reports of Forecasting Officers' Conference regarding classification of Low Pressure Areas)

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1. Recommendations of sub-committee – First Forecasting Officers' Conference, February 1951.

To facilitate classification of the depressions and cyclonic storms, the following Table is recommended for adoption:–

| | Shallow depression | Depression | Deep Depression | Cyclonic Storm | Severe Cyclonic Storm |
|---|---|---|---|---|---|
| Maximum wind speed observed or inferred to be existing | upto 16 knots | 17–21 knots | 22–27 knots | 28–40 knots | 41 knots or more |
| Pressure *deficiency | 2–4 mbs | 4–7 mbs | 7–11 mbs | 11–16 mbs | 16 mbs or more |
| Number of closed isobars at intervals of 2 mbs. | 2 | 3 | 4 or 5 | 6 to 8 | More than 8 |

* Pressure departure outside the outermost closed isobars is to be subtracted from the departure at the centre to get the effective pressure deficiency.

N.B.: In classifying a tropical circulation, the main consideration should be the wind speed, observed or inferred to be existing. It is, however, necessary to take the pressure deficiency at the centre or the total number of closed isobars into consideration. It has been observed that the same pressure deficiency is associated with stronger winds at the lower latitudes compared to those at higher latitudes. Further, the same pressure deficiency is associated with less strong winds during the monsoon months than during other periods.

2. Recommendations of sub-committee – Third Forecasting Officers' Conference, April 1960.

(b) Item 6.1:
Classification of cyclonic storms:

The sub-committee reviewed the past practices regarding the criteria used in defining cyclonic storms and took note of the modifications in the limiting wind speeds brought into effect from 1.10.54, as a result of implementation by the Department of Rec. No. 27 of CMM-I. It was noted that while the Department was using the velocity range 28-40 knots for declaration of a cyclonic storm prior to 1.10.54, the range was raised to 34-47 knots according to the modified criteria. Corresponding changes have occurred in respect of other pressure systems also. It was unanimously agreed that the main criteria for defining cyclonic systems should be the wind speed. The terms 'cyclonic storm' and 'severe cyclonic storm' are already well defined from this point of view and there has been little difference of opinion between the forecasting offices in describing the 'cyclone' or a 'severe cyclone' when the same observational material was available. Marked cases of deviation in the description of systems have, however, occurred in respect of pressure systems of lower intensity. While according to CMM – I, all pressure systems with a velocity of 33 knots and below are treated as tropical depressions the departmental offices have been sub-dividing the systems in this range into deep depression, depression, shallow depression, marked low pressure area, low pressure area and unsettled conditions. There appears to be no need to use such a variety of terms particularly because the variations in the severity of weather between some of these systems are insignificant. After careful consideration the committee felt that there need be only two stages in the naming of the development of a pressure system before it reaches the storm stage. The committee has carefully considered the term 'unsettled conditions' as used in the past and has come to the conclusion that this should be dropped from the Department's terminology. When there is no closed circulation detectable in the initial stages there should be no objection in using the terms 'trough of low pressure' as defined in Poona DDGF UO No. W337 dated 19.6.54 to all RCs (Appendix)*. Also there should be no objection to using terms such as easterly wave as and when occasion demands.

/ * Not reproduced

The Committee, therefore, recommends the following classification of the various low pressure systems when closed circulations are detectable on the sea level synoptic charts.

Over the sea:

(1) Low pressure area – wind speed not exceeding 17 knots (B.F. 4)
Depression – Speed 18 – 33 knots (B.F. 5,6,7)
Cyclonic Storm – Speed 34 – 47 knots (B.F. 8 and 9)
Severe Cyclonic Storm – speed 48 knots and above (B.F. 10 and above)

(2) In the absence of wind reports the committee recommends the following relation between wind force and pressure gradient or pressure deficiency as a guide to estimate the wind in the area of the disturbance.

| Wind Force | Pressure gradient measured from the centre | Relative pressure deficiency at the centre and at a point 250 kms from the centre |
|---|---|---|
| 4 B.F. | 5 mbs. per 250 kms | below 5 mbs |
| 5,6,7 B.F. | Above 5 mbs to 13 mb per 250 kms | 5-13 mbs |
| 8 and 9 B.F. | Above 13 mbs to 18 mbs per 250 kms | 13-18 mbs |
| 10 B.F. and over | Above 18 mbs per 250 kms | 18 mbs and above |

Over land: The criteria defined for sea area above may be applied to pressure systems over land also, subject to the condition that the wind concerned should be wind observed at 0.9 km asl instead of the surface wind.

3. Recommendations of sub-committee – Seventh Forecasting Officers' Conference, March 1972.

Item 4.2 Classification of low-pressure systems : Need for adherence to specifications

The following are the recommendations of the Sub-Committee:

i) The Forecasting Officers' Conference 1960 has clearly stated that wind speed alone is the main criterion in defining the intensity of the tropical disturbance. The pressure gradient is mentioned only as an indirect aid to wind estimation in the absence of wind reports. The sub-committee therefore feels that the existing criteria need no change.

ii) The word "wind" used in the definition may be qualified by the expression "observed or inferred". This was the practice before 1960 (see recommendation of F.O's Conference, 1951). Satellite picture now provides an additional tool to infer the wind speeds.

iii) The criteria in use does not specifically state the location of the region of the characteristic wind strength of the system with reference to the centre of the tropical disturbances. Studies have shown that the characteristic wind speed is not more than 2 or at best 3 degrees away from the centre. Experienced forecasters are aware of this. To make the criteria complete and more specific, there is a necessity to include in our definition the distance within which (with reference to the centre) the characteristic wind speed should be observed. However, the sub-committee feels that this problem merits a more detailed study after which only any such amplification in the definition can be made.

iv) When the disturbance is over land, the 0.9 km asl winds are likely to be meagre over the area. As suggested by DDGF in his address on the opening day, the Laplacian of the pressure field may be tried as a measure of intensity of the disturbance. An experiment on this line may be made and on the basis of the findings, suitable criteria may be laid down for disturbances over land.

Extracts from Forecasting Circular No.1 of 1972 :

.... .... ....

3.1.3 Pressure Centres

| Feature | Wind speed observed or estimated (knots) | Symbols: Mono-chromatic | Symbols: Poly-chromatic | |
|---|---|---|---|---|
| Low | Not exceeding 17 kts. | **L** | **L** | Red |
| Depression | 17 – 27 kts | **D** | **D** | Red |
| Deep depression | 28 – 33 kts | **DD** | **DD** | Red |
| Cyclonic storm | 34 – 47 kts | **CS** | **CS** | Red |
| Severe cyclonic storm | 48 – 63 kts | **SCS** | **SCS** | Red |
| Severe cyclonic storm with a core of hurricane winds | 64 kts and above |  |  | Red |

## APPENDIX - II

MODEL CHECK SHEET*

1. Date . . . . . . . . . . . Time . . . . . Based on chart for . . . . . . .Z

2. Intensity of disturbance:
Depression/ Deep Depression/ Cyclonic Storm/ Severe Cyclonic Storm/ Severe cyclonic storm with a core of hurricane winds
   i) Basis
      a) Ship reports
      b) Coastal or island stations
      c) Satellite
      d) Radar
      e) Aircraft Reconnaissance
      f) Microseisms

   ii) Whether 'eye' reported
   iii) Maximum winds (actual report or from satellite nomogram)
   iv) Lowest pressure (actual report or from Fletcher's formula) and pressure departures.

3. Centre of disturbance - Lat(N) - Long(E)

   Accuracy of centre fixation - within ................ degree

   Basis — Accuracy (good/fair/ poor)

   a) Ship reports
   b) Coastal or island station
   c) Satellite
   d) Radar
   e) Aircraft Reconnaissance

4. Forecast development/weakening -
   a) Pressure changes
   b) Sea surface temperature
   c) Vertical wind shear
   d) Upper divergence
   e) Satellite pictures (i)Cirrus outflow
      (ii) Feeder band
   f) Is the area climatologically favourable for development/weakening.

5. Past movement -
   a) Past 12 hrs
   b) Past 24 hrs

6. Forecast movement - Direction . . . . . . . . . . Speed . . . . . knots
   Basis -
   a) Extrapolation of present movement
   b) Climatology - (i) IITM Forecast
      (ii) NHAC Forecast
   c) 200-150 mb flow pattern
   d) 700-500 mb flow pattern
   e) Pressure changes
   f) Recurvature - (i)Is a westerly trough approaching?
      (ii) Is storm slowing down during past 12/24 hrs?

7. If expected to cross coast during forecast period -
   i) maximum winds
   ii) storm tide
   iii) crossing at time of high tide/low tide

8. Any other remarks:

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* The Check Sheet given here is a model one. This may be amended or improved to suit the needs of individual offices.

## APPENDIX - III

### Some points regarding the utilisation of ships observations in synoptic meteorological work*

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1. Ships observations are generally available only from sea areas through which well-frequented shipping lanes lie. Over other areas, observations are very meagre; some portions of the sea area remain completely data-void. The degree of reliability of the various parameters reported by ships and the more common errors in them will be described here, so that forecasters are aware of them while using ships data in operational work and are able to spot out doubtful observations and check them. It is one of the important items in practical storm warning work, and one gets a knack for it only by experience.

2. The main sources of error that creep into ships observations are:-

i) Inherent difficulties of reporting accurately some elements like pressure and cloud heights
ii) Errors due to mutilations in transmission since the observational telegram passes through a number of intermediate handling stations before it finally reaches the meteorological office
iii) Possible inexperience of the marine officer on board the ship

We will now discuss the above listed possible sources of error in important elements of ships' observation (including position of the ship).

3. The elements in a ships' observations which are of greater importance in the operational work are,

a) wind b) pressure c) wave d) weather e) sea surface temperature

Of these, the most important one is the wind; sometimes it may be very crucial. Of course, the position of the ship and time of observation are also important.

4. (a) **Wind:** Wind direction and speed reported by ships are considered to be accurate, even though they might have been obtained without a windwane and anemometer. The existing code has provision for reporting wind speed either in knot or in m.p.s., though the number of observations in m.p.s. we come across is very small. However, this possibility of a ship reporting the winds in m.p.s. should be kept in mind when the wind speed reported by a ship is found doubtful. Sometimes special observations from ships in storm areas are received in plain language and in these observations the wind direction may be reported in 16 or 32 points of the compass and the wind speed may be in B.F. Since most wind observations are estimates based on the state of the sea etc., observations during dark nights may have to be taken with some caution.

(b) **Pressure:** Though pressure is a very important observation for analysis of the surface charts, pressure values reported by ships are often not very reliable. Many ships possess only an aneroid of old type which frequently changes its zero reading. Mercury barometers at sea are subject to pumping errors, ventilation effect etc; in disturbed weather, pumping error may not be negligible. Ships using precision aneroids may be expected to give reliable readings. Another

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* Shri J.M. Khorkao, Meteorologist, was associated with the preparation of this note.

possible error is the omission to reduce the bar reading to sea level, which could result in a reported bar value (PPP) too low by 1 to 2 mb, as in most ships the height of the barometer is about 30 to 60 ft. above sea level.

Ships reporting observations in plain language may sometimes use inches instead of mb to report the pressure.

If the ship's report does not exactly correspond to the time of the chart, suitable diurnal correction (refer Appendix III a) will have to be applied to the pressure values. Besides, the movement of the ship during the time interval between the time of observation and the time of the chart, should also be taken into account, particularly if the ship is travelling fast.

(c) Wave Observations: The wave observations are of two types - one, the sea wave generated locally and the other, swell wave. In respect of the sea waves, only the period and height are reported. When the wind speed (ff) reported by a ship is doubtful, it may be checked with the height of the sea waves.

(d) Sea surface temperature: Certain discrepancies in reported sea surface temperatures are possible because of the different methods adopted for measuring sea temperature. However, these discrepancies are not of a very serious nature for operational work.

(e) Position of ships: Position of ships plotted on the charts, sometimes, are in error. One of the main errors is the plotting of the ships in the wrong quadrant - as for instance, ships to the south of equator being plotted in the northern hemisphere. The mistakes in the position of the ship can be verified by checking it with earlier reports from the same ship. It would be a good practice if a time sequence of the ships observations is also plotted separately (just like hourly observations of land stations) in respect of such ships which are in the field of a disturbance so that the changes in wind etc. reported by the ships could be better appreciated visually by the forecaster. Even when there is no storm or depression, the marked changes in wind direction from a sequence of observations from the same ship will enable the forecaster to place trough line etc. accurately on the chart.

5. For an efficient storm warning service the following aids will be very helpful.

i) A register of corrections to ships barometer in respect of ships which normally ply in Arabian Sea and Bay of Bengal.

ii) A statement of performance of various ships during the recent few years, which should be periodically updated.

iii) International list of selected and supplementary ships (WMO publication).

iv) Alphabetical list of call signs of Maritime mobile service (published by International Telecommunication Union) - giving call signs of ships.

# APPENDIX - III(a)

LOCAL TIME AT VARIOUS LONGITUDES CORRESPONDING TO 0000 GMT

| 40°E | 45°E | 50°E | 55°E | 60°E | 65°E | 70°E | 75°E | 80°E |
|---|---|---|---|---|---|---|---|---|
| 0240 | 0300 | 0320 | 0340 | 0400 | 0420 | 0440 | 0500 | 0520 |

| 85°E | 90°E | 95°E | 100°E | 105°E | 110°E |
|---|---|---|---|---|---|
| 0540 | 0600 | 0620 | 0640 | 0700 | 0720 |

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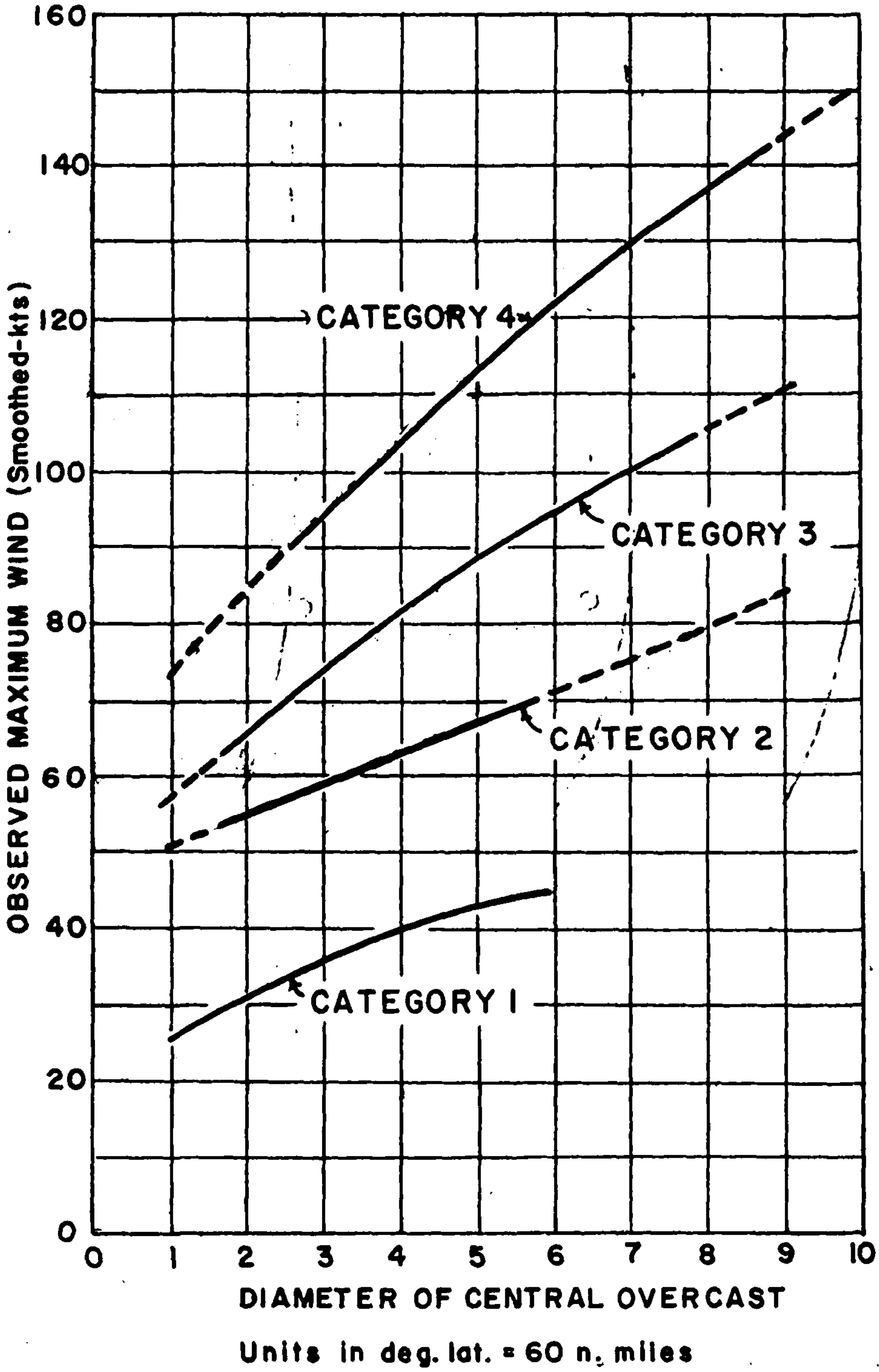
DAILY RANGE OF BAR FROM MIDNIGHT - NOON - MIDNIGHT (LOCAL TIME)

| | | | |
|---|---|---|---|
| 0000 — +0.5 mb | 0600 — +0.1 mb | 1200 — +0.5 mb | 1800 — −1.3 mb |
| 0020 — +0.3 | 0620 — +0.4 | 1220 — +0.2 | 1820 — −1.0 |
| 0040 — +0.2 | 0640 — +0.6 | 1240 — −0.1 | 1840 — −0.7 |
| 0100 — +0.0 | 0700 — +0.9 | 1300 — −0.4 | 1900 — −0.6 |
| 0120 — −0.1 | 0720 — +1.1 | 1320 — −0.7 | 1920 — −0.3 |
| 0140 — −0.3 | 0740 — +1.3 | 1340 — −1.0 | 1940 — −0.1 |
| 0200 — −0.4 | 0800 — +1.5 | 1400 — −1.2 | 2000 — +0.1 |
| 0220 — −0.5 | 0820 — +1.6 | 1420 — −1.4 | 2020 — +0.3 |
| 0240 — −0.6 | 0840 — +1.7 | 1440 — −1.6 | 2040 — +0.5 |
| 0300 — −0.7 | 0900 — +1.9 | 1500 — −1.7 | 2100 — +0.7 |
| 0320 — −0.7 | 0920 — +1.9 | 1520 — −1.8 | 2120 — +0.7 |
| 0340 — −0.7 | 0940 — +1.9 | 1540 — −1.9 | 2140 — +0.9 |
| 0400 — −0.7 | 1000 — +1.8 | 1600 — −1.9 | 2200 — +0.9 |
| 0420 — −0.6 | 1020 — +1.7 | 1620 — −1.9 | 2220 — +0.9 |
| 0440 — −0.5 | 1040 — +1.5 | 1640 — −1.8 | 2240 — +0.9 |
| 0500 — −0.4 | 1100 — +1.3 | 1700 — −1.7 | 2300 — +0.8 |
| 0520 — −0.2 | 1120 — +1.1 | 1720 — −1.6 | 2320 — +0.7 |
| 0540 — 0.0 | 1140 — +0.7 | 1740 — −1.4 | 2340 — +0.6 |

APPENDIX - IV

NOMOGRAM FOR OBTAINING MAXIMUM WINDS OF STAGE X TROPICAL DISTURBANCES



## APPENDIX – V

Extracts from the Report of the Seventh Conference of Forecasting Officers', March 1972.

Item 4.1 : Use of satellite pictures for delineation of Centres of depressions/ cyclones in significant weather charts.

The Sub-Committee carefully examined the available literature on the subject of tropical disturbances as seen in satellite pictures, their centering and estimation of maximum winds. Our own experience in this field during the past few years was also taken note of. The system adopted by the department for classification of satellite pictures of tropical disturbances is the same as the one currently in use at the National Environmental Satellite Centre, Washington. This system is a combination of earlier two classification schemes, after incorporating later experience.

The points considered by the Sub-Committee were:

i) Determination of centre of tropical disturbance from the satellite pictures,

ii) the reliability of the centering from the pictures,

iii) inherent limitations of satellite centering,

iv) the intensity of the disturbances as revealed by satellite pictures,

v) limitations of the intensity determination,

vi) the validity of the nomogram used to determine the maximum wind speeds in stage X storms.

Some of the considerations that led to the recommendations are given in the Appendix V a. for reference.

The Sub-Committee, after a careful examination of the whole question, makes the following Recommendations*:-

1. The satellite pictures provide a very useful information, particularly over sea areas where ships' observations are very meagre or totally absent. Satellite data should be treated as an additional observational aid, although there is some amount of subjectivity that cannot be altogether avoided in satellite picture interpretation.

2. The satellite information should be judiciously blended with the conventional observations, such as those from ships, coastal stations, inland stations, radar reports, aircraft reports, etc. to get the best integrated picture of the tropical depression or storm.

3. Unless such conventional observations are available from the close proximity of the depression or storm centre, maximum weightage should be given to the satellite information, both in regard to determination of the centre and the intensity. In this connection, forecasters should keep in mind the structure of the tropical storm and depressions as revealed by aircraft reconnaissance, radars and satellite data.

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* Recommendations under examination.

4. The nomogram for the determination of maximum wind can be relied upon with a good degree of confidence over the Indian sea area also.

5. The following equivalents of satellite picture categorization (stages A and B, C and X) in terms of the corresponding synoptic categorization (low pressure areas, depression, cyclonic storms etc.) may be adopted:-

| | | | |
|---|---|---|---|
| Stage A | : | Low pressure area or wave | |
| Stage B | : | Well marked low pressure area or depression. | |
| Stage C– and C | : | Depression to deep depression | |
| Stage C+ | : | Cyclonic storm | |
| Stage X | : | Cat.2 : | Cyclonic storm or severe cyclonic storm, depending upon the maximum wind as obtained from nomogram; hurricane speeds not excluded. |
| | | Cat.3 : | Severe cyclonic storm, hurricane winds if nomogram suggests. |
| | | Cat. 4 : | Severe cyclonic storm with a core of hurricane winds. |
| | | Note: | Stage X Cat.1 is seldom used. |

6. The recommendation with reference to centering of the disturbances from the satellite picture is given below:

| | | |
|---|---|---|
| Stage A | : | No centre |
| Stage B | : | ill-defined centre |
| Stage C– C and C+ | : | Definite centre |
| Stage X | : | Cat.2, 3 and 4 : Definite centre. |

Note: Reliability of the centering from xxx pictures and the limitations of satellite centering are given in the Appendix I. The general conclusion is that centre should be taken as correct to 1/2 degree of lat./long. if (i) the eye is visible or if the centre is based on cumuliform bands as in stages C– C and C+ and (ii) if the gridding is based on land marks. Otherwise the centre may be out by as much as 1 to 2 degrees of Lat./Long.

7. The APT bulletins issued on occasions of tropical disturbance should contain details such as the confidence in gridding, presence of land marks in the picture, quality of the picture, whether the disturbance is towards the edge of pictures etc. This will enhance the utility of the bulletins in operational forecasting by providing the operational forecasters necessary information as to the degree of confidence he can attach to satellite picture information.

8. In the pre-storm stages, though winds close to the centre are relatively weak, winds far away from the centre under areas of heavy convection may be considerably stronger and can reach speeds of 40 kts or more. This feature may be kept in view by the operational forecaster, while utilising satellite picture information.

9. Satellite picture interpretation requires constant familiarity with satellite pictures and experience in the field. It will, therefore, be necessary that, to make the best use of satellite picture information in storm warning work, suitably trained and qualified persons should be posted to satellite units.

Item 4.2 : Classification of low-pressure systems : Need for adherence to specifications.

The following are the recommendations of the Sub-Committee :

i) The Forecasting Officers' Conference 1960 clearly stated that wind speed alone is the main criterion in defining the intensity of the tropical disturbance. The pressure gradient is mentioned only as an indirect aid to wind estimation in the absence of wind reports. The Sub-committee therefore feels that the existing criteria need no change.

ii) The word "wind" used in the definition may be qualified by the expression "observed or inferred". This was the practice before 1960 (see recommendation of F.O's Conference 1951). Satellite picture now provides an additional tool to infer the wind speeds.

iii) The criteria in use does not specifically state the location of the region of the characteristic wind strength of the system with reference to the centre of the tropical disturbances. Studies have shown that the characteristic wind speed is not more than 2 or at best 3 degrees away from the centre. Experienced forecasters are aware of this. To make the criteria complete and more specific, there is a necessity to include in our definition the distance within which (with reference to the centre) the characteristic wind speed should be observed. However, the Sub-committee feels that this problem merits a more detailed study after which only any such amplification in the definition can be made.

iv) When the disturbance is over land, the 0.9 km asl winds are likely to be meagre over the area. As suggested by DDGF in his address on the opening day, the Laplacian of the pressure field may be tried as a measure of intensity of the disturbance. An experiment on this line may be made and on the basis of the findings, suitable criteria may be laid down for disturbances over land.

# APPENDIX - V (a)

1. Reliability of centering in the picture

   Stage B : Low reliability

   Stage C : High reliability

   Stage X : Cat. 2 : reliable

   Cat. 3 and 4 ( Highly reliable if eye is seen in the picture. However, ( if eye is not clearly visible due to poor picture ( quality or eye being obscured by some clouds, the centre ( determined by the bands is less reliable.

2. Limitation in satellite centering

   (1) Gridding errors

   (2) Poor organization of cloud systems, uniform brightness of clouds and poor picture quality lead to inaccuracies in centering

   (3) Subjectivity of APT Analyst

3. Limitations in intensity determination

   (1) So far as Stages A and B are concerned, the intensity may be taken as given in recommendation No. 5.

   (2) For Stages C- and C, though NESC 51 "Application of Met. Satellite Data in Analysis and Forecasting", gives wind speeds of upto 40 knots., In view of the fact that the centre is still outside the overcast area, which is generally the characteristics of the pre-storm stage, we may take stages C- and C to correspond to deep depression only and not to cyclonic storms.

   (3) Stage C+ : Though NESC 51 gives a range of speed upto 65 kts, still, as the centre is only just inside the overcast and the outflow is not well-marked in all quadrants, we may, for the present, keep this stage to correspond to cyclonic storms only.

4. Validity of the nomogram

The authors (Fritz, Hubert and Timchalk) of the nomogram themselves have clearly stated that the nomogram is semi-objective, based on empirical considerations. Both the size of the overcast and the classification into a given category are somewhat subjective. It is, however, significant that experienced analysts agree on classifications in a majority of cases.

Studies so far conducted over India also support that the nomogram for maximum wind speed is good within the limitations and subjectivity inherent in the nomogram itself.

The scatter about the curves is about ± 15 knots. The subjectivity involved in estimating the category and the diameter, may introduce another error. However, experienced analysts usually do not differ in categorization if the picture quality is good. The error in estimating the diameter may lead to about 10 knots differences for each degree of error in diameter estimate. However, as mature storms (Cat. 3 and 4) have a generally clear-cut overcast, the diameter estimation error is mainly in Cat.2. The operational forecasters should keep in mind these errors inherent in the system while applying the nomogram.

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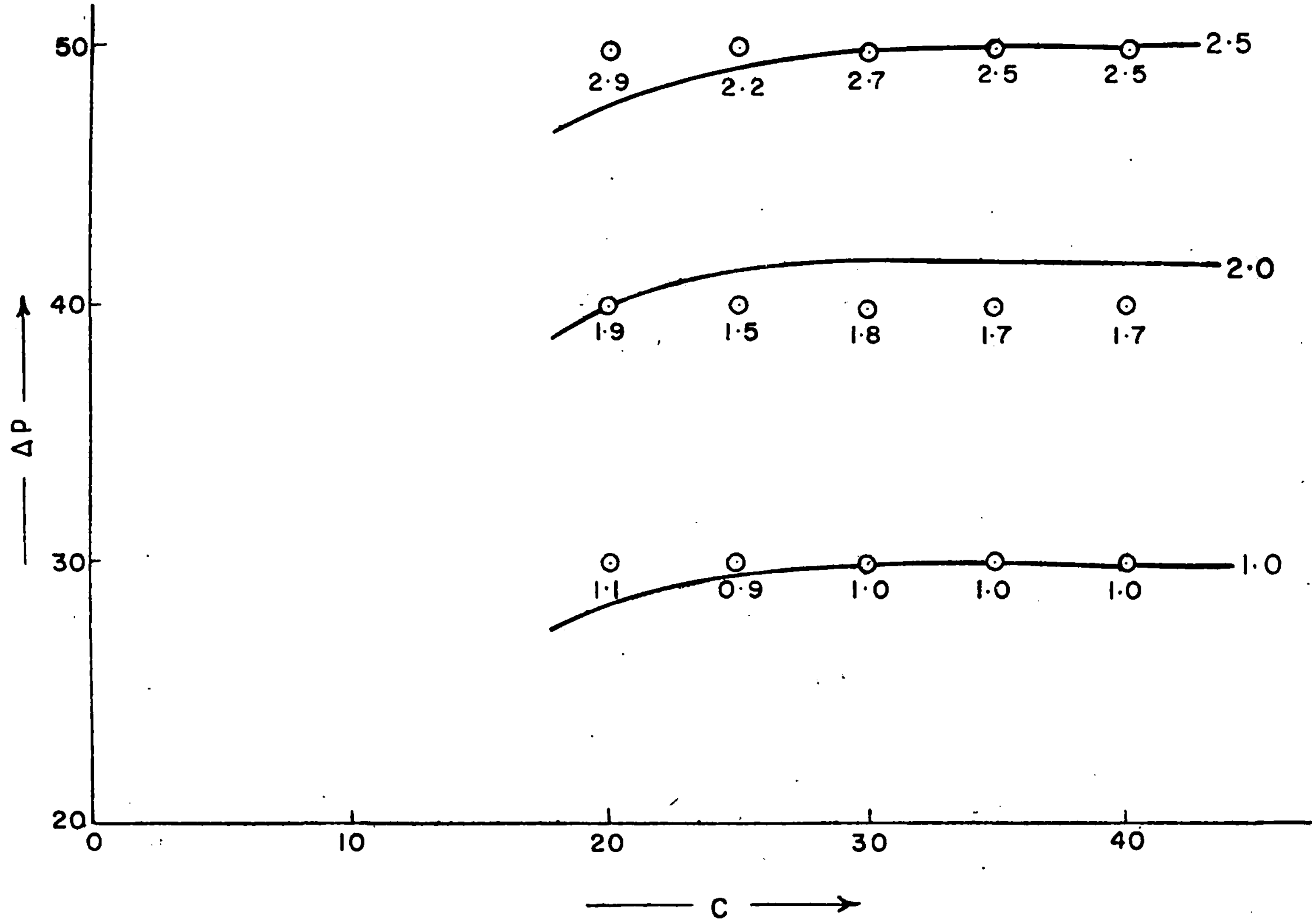
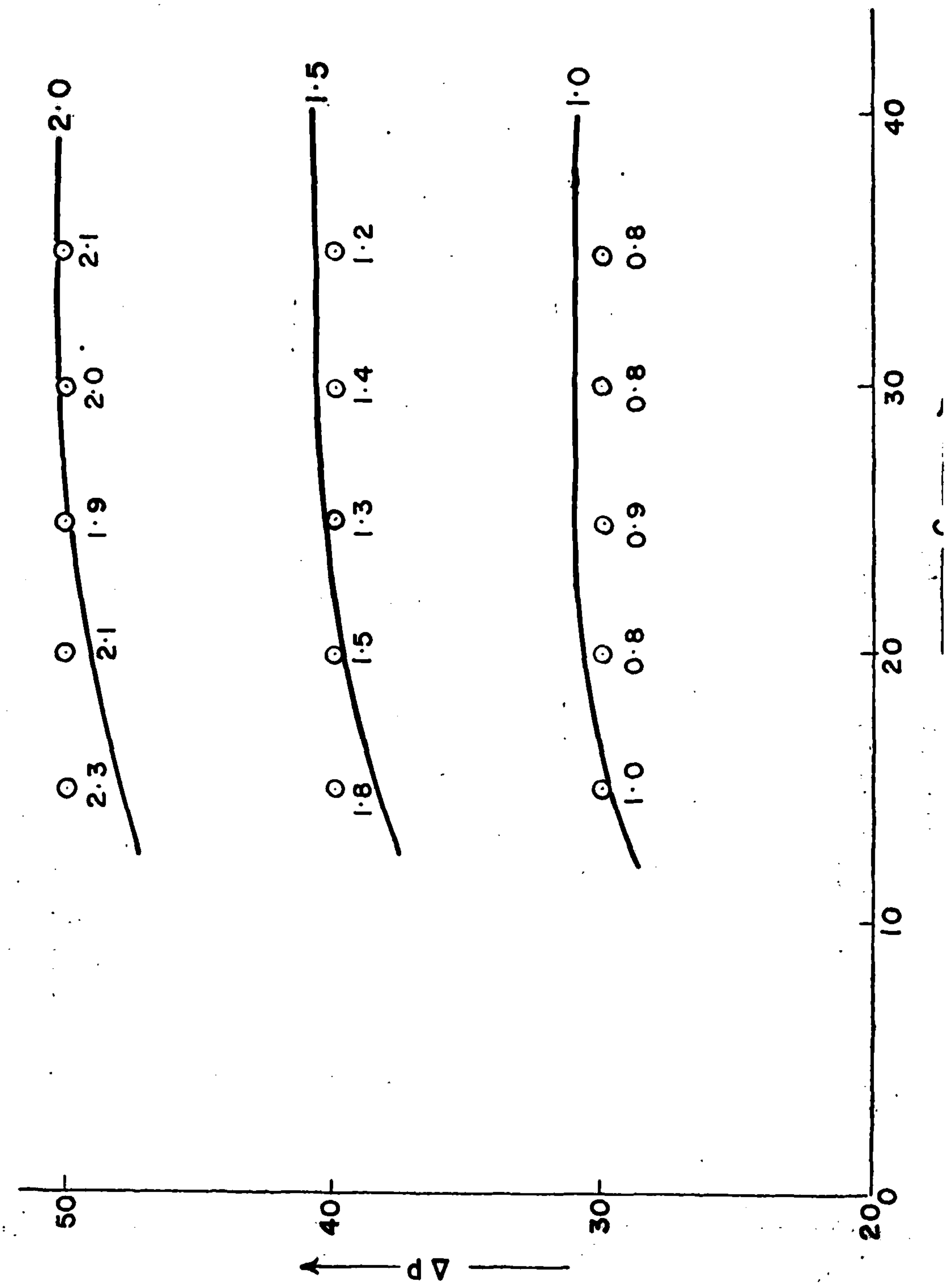
## APPENDIX VI

### SURGE PREDICTION NOMOGRAM*
### NORTHEAST TRACK (I)

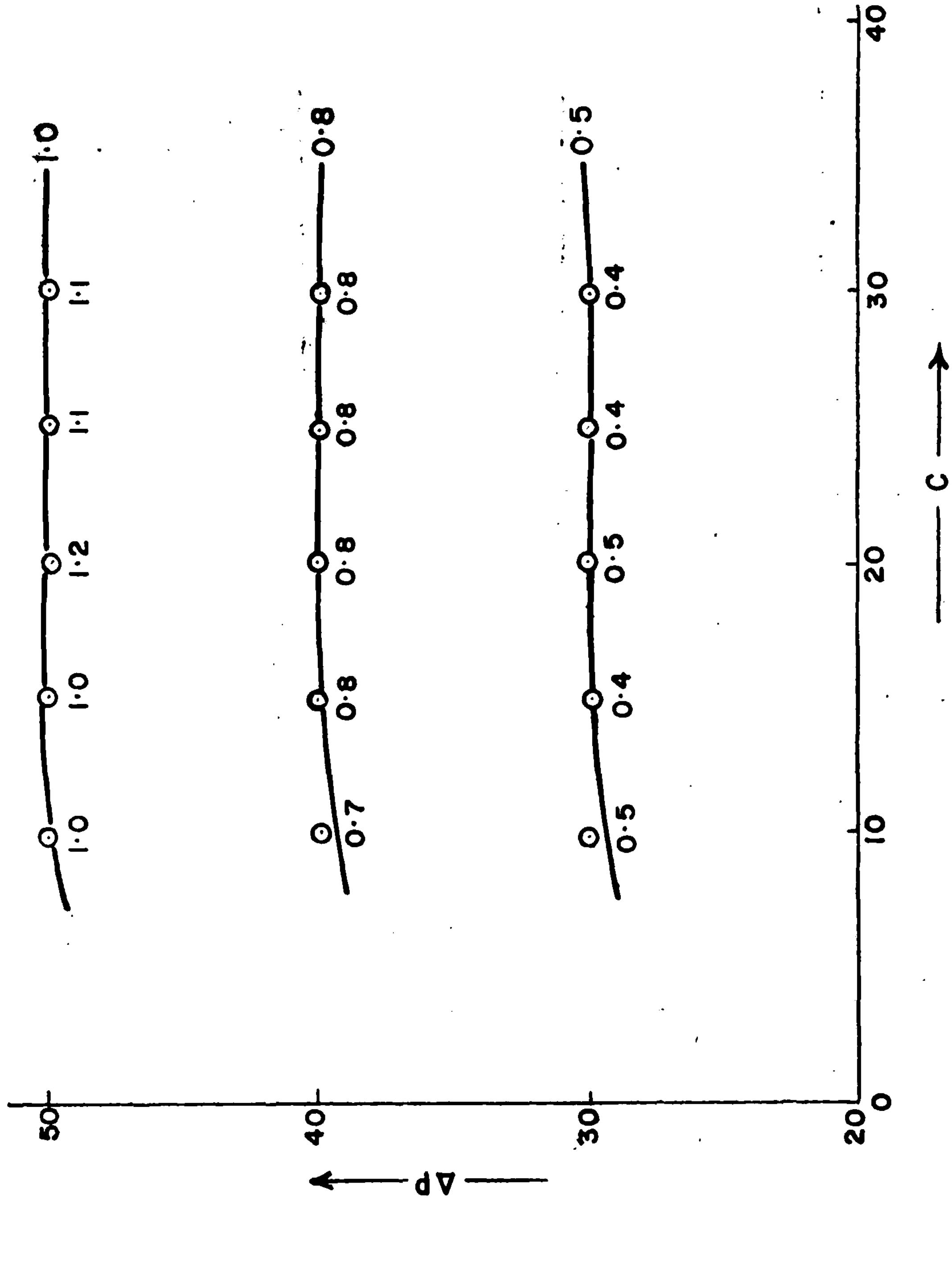


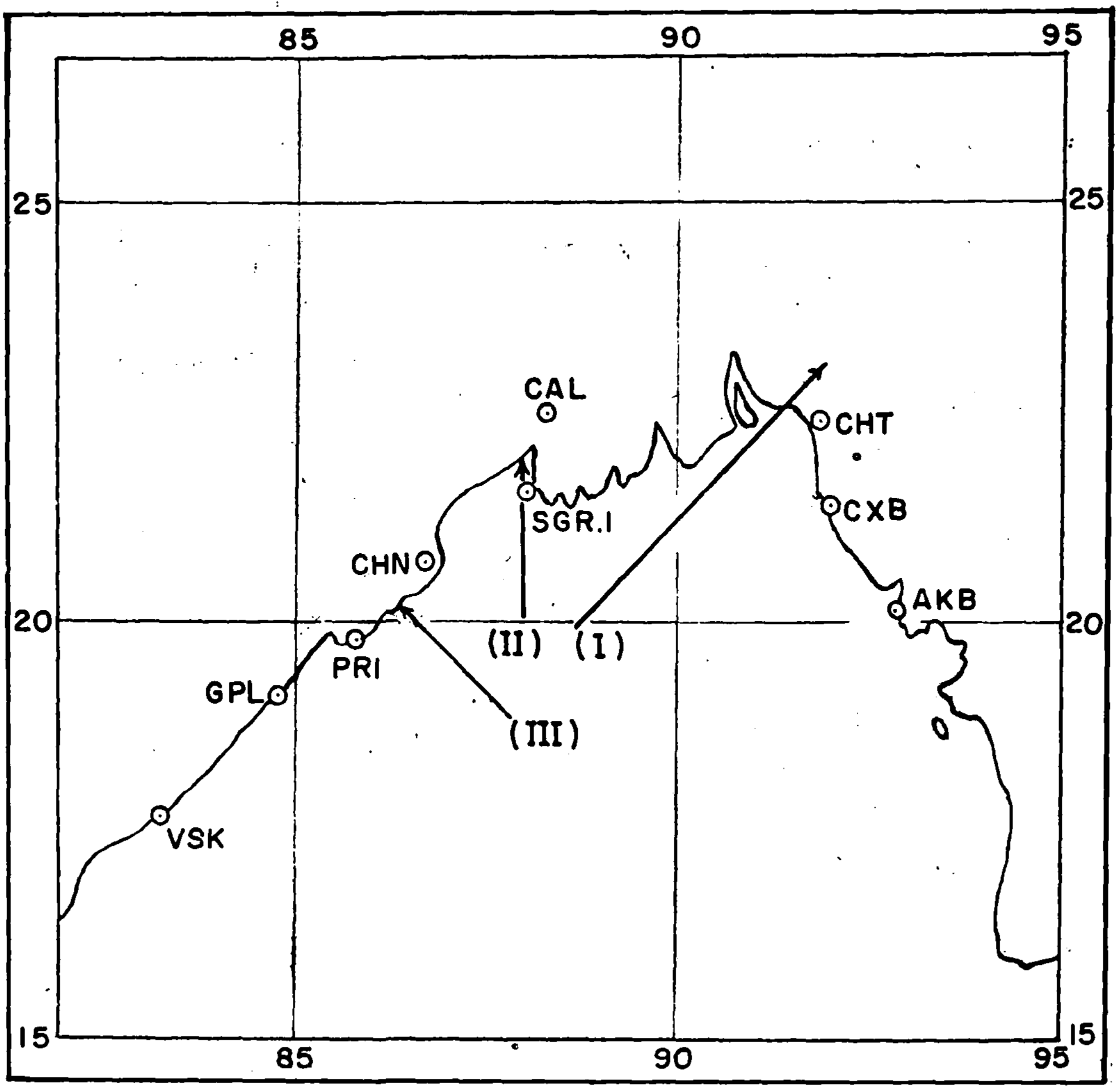

* From "Storm Surges in the Bay of Bengal" by P. K. Das, M. C. Sinha and V. Balasubramaniam (under publication)

SURGE PREDICTION NOMOGRAM
NORTH TRACK (II)



SURGE PREDICTION NOMOGRAM
NORTHWEST TRACK (III)






IDEALIZED STORM TRACKS (I), (II) & (III) FOR SURGE PREDICTION DIAGRAM

## INSTRUCTIONS FOR THE USE OF SURGE PREDICTION NOMOGRAMS

1. Abscissa refers to the expected uniform speed of the storm movement (C) in Km $hr^{-1}$.

2. The quantity '$\Delta p$' in the ordinate represents the difference between the pressure at the outer periphery of the storm and its estimated central pressure in mb.

3. Isopleths in the nomogram give the predicted height of maximum storm surge in metres at the time of landfall.

4. The predicted heights of storm surge do not include astronomical tides.

5. Predicted maximum surge height refers to an area about 30 to 50 km to the right of the land-fall of the storm.

6. It may be pointed out that local topography such as river estuaries, concave coastal area, off shore islands etc. can affect the local spot values of surge heights. These aspects will be considered in future studies.

7. The surge heights $\zeta$ may be also calculated by the following general equation derived on the basis of the nomograms.

$$\zeta = a_0 \Delta p + a_1 \Delta p^2 + a_2 C$$

where the numerical values of $a_0$, $a_1$ and $a_2$ are as follows:-

| S.No. | Track | $a_0 \times 10^3$ | $a_1 \times 10^3$ | $a_2 \times 10^3$ |
|---|---|---|---|---|
| 1. | Northeast (I) | 16.0 | 0.77 | − 5.30 |
| 2. | North (II) | 29.0 | 0.40 | −14.70 |
| 3. | Northwest (III) | 4.1 | 0.34 | + 1.70 |

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(Revision of NOAA TM NESS 36).

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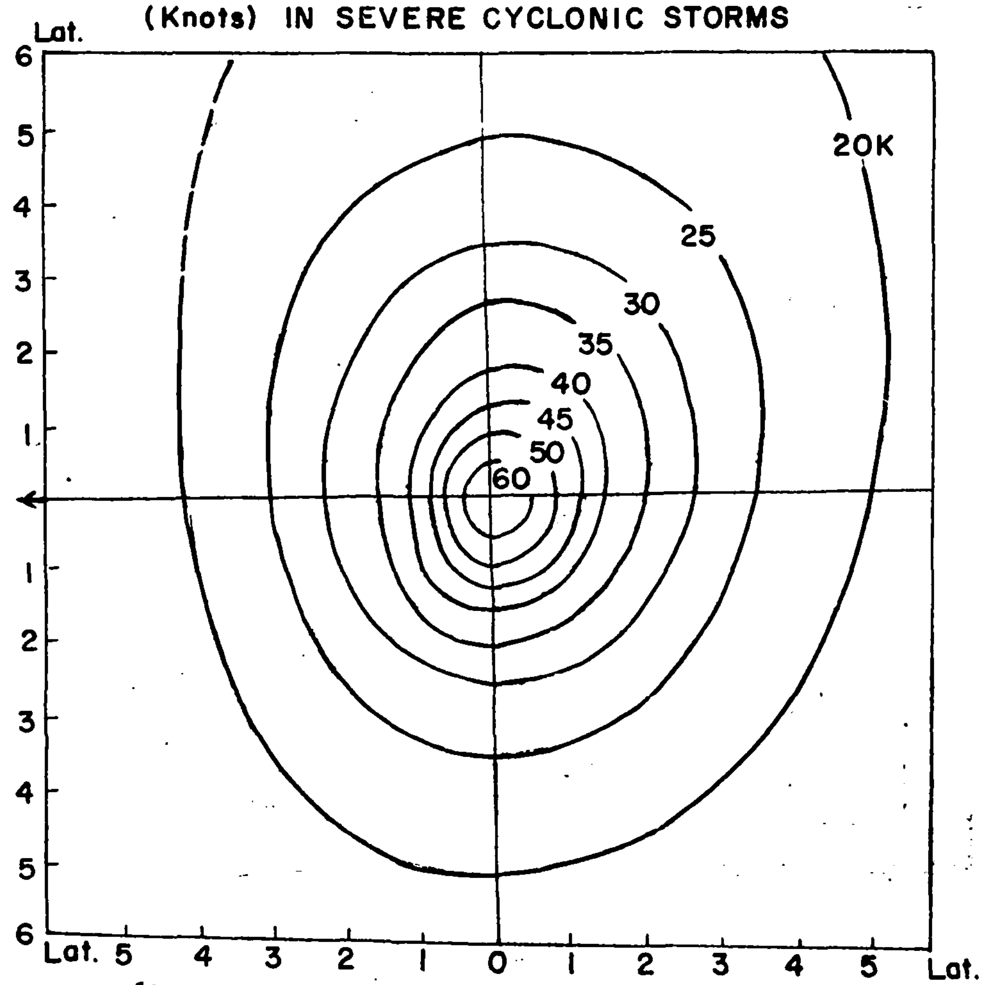
# DIAGRAMS

FIG. 4·1 DISTRIBUTION OF MEAN SURFACE WIND SPEED (Knots) IN SEVERE CYCLONIC STORMS




From: "The Surface Structure of Tropical cyclones in the Indian area" by P. Koteswaram and S. Gaspar IJMG (1956) Vol. 7, No. 4, pp. 339-352.

Arrow indicates direction of movement of storm

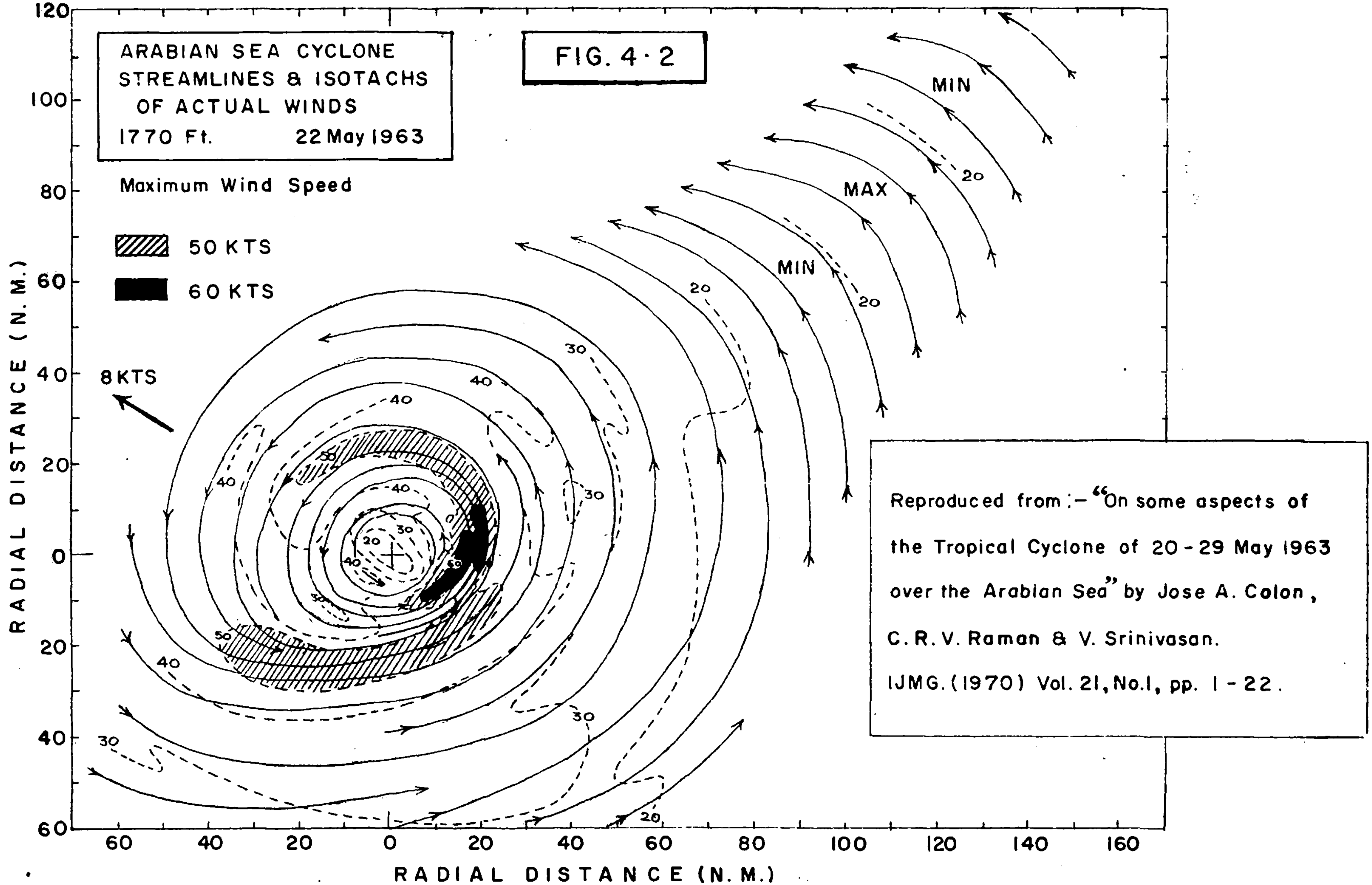
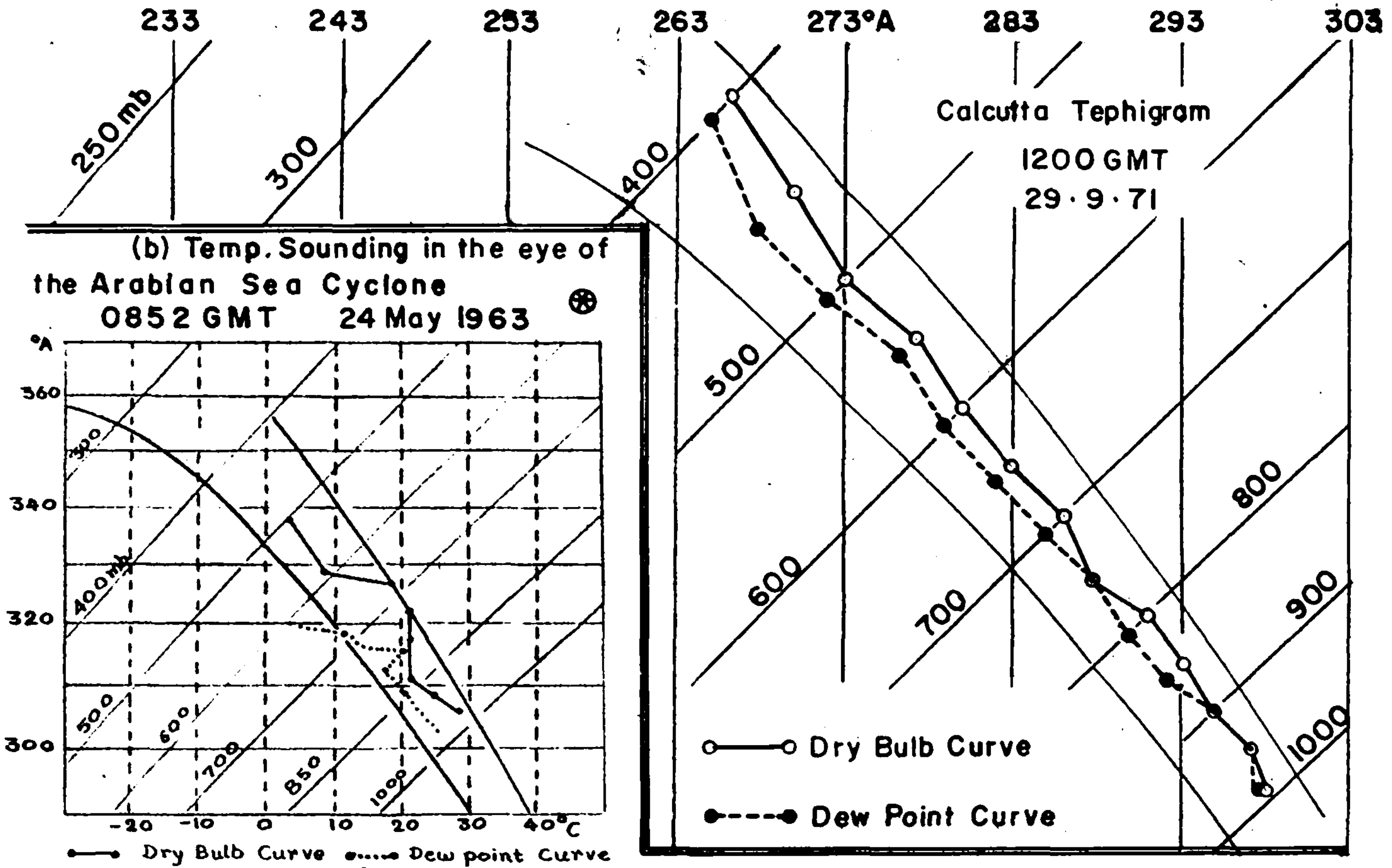

ARABIAN SEA CYCLONE
STREAMLINES & ISOTACHS
OF ACTUAL WINDS
1770 Ft. 22 May 1963
Maximum Wind Speed
50 KTS
60 KTS
8 KTS
MIN
MAX
MIN
RADIAL DISTANCE (N. M.)
RADIAL DISTANCE (N. M.)
Reproduced from :- "On some aspects of the Tropical Cyclone of 20 - 29 May 1963 over the Arabian Sea" by Jose A. Colon, C. R. V. Raman & V. Srinivasan. IJMG. (1970) Vol. 21, No.1, pp. 1 - 22.

FIG. 4·2

FIG. 4.3 RADIOSONDE ASCENTS IN THE FIELD OF CYCLONIC STORMS IN INDIA

(a) Position of storm at 1200 Z of 29 Sept. 71 about 50 km. south of Calcutta.




⊛ Reproduced from: "On some aspects of the Tropical Cyclone of 20-29 May 1963 over the Arabian Sea" by Jose A. Colon, C. R. V. Raman & V. Srinivasan. IJMG (1970) Vol. 21, No. 1, pp. 1-22.

# OCTOBER (1891-1970)

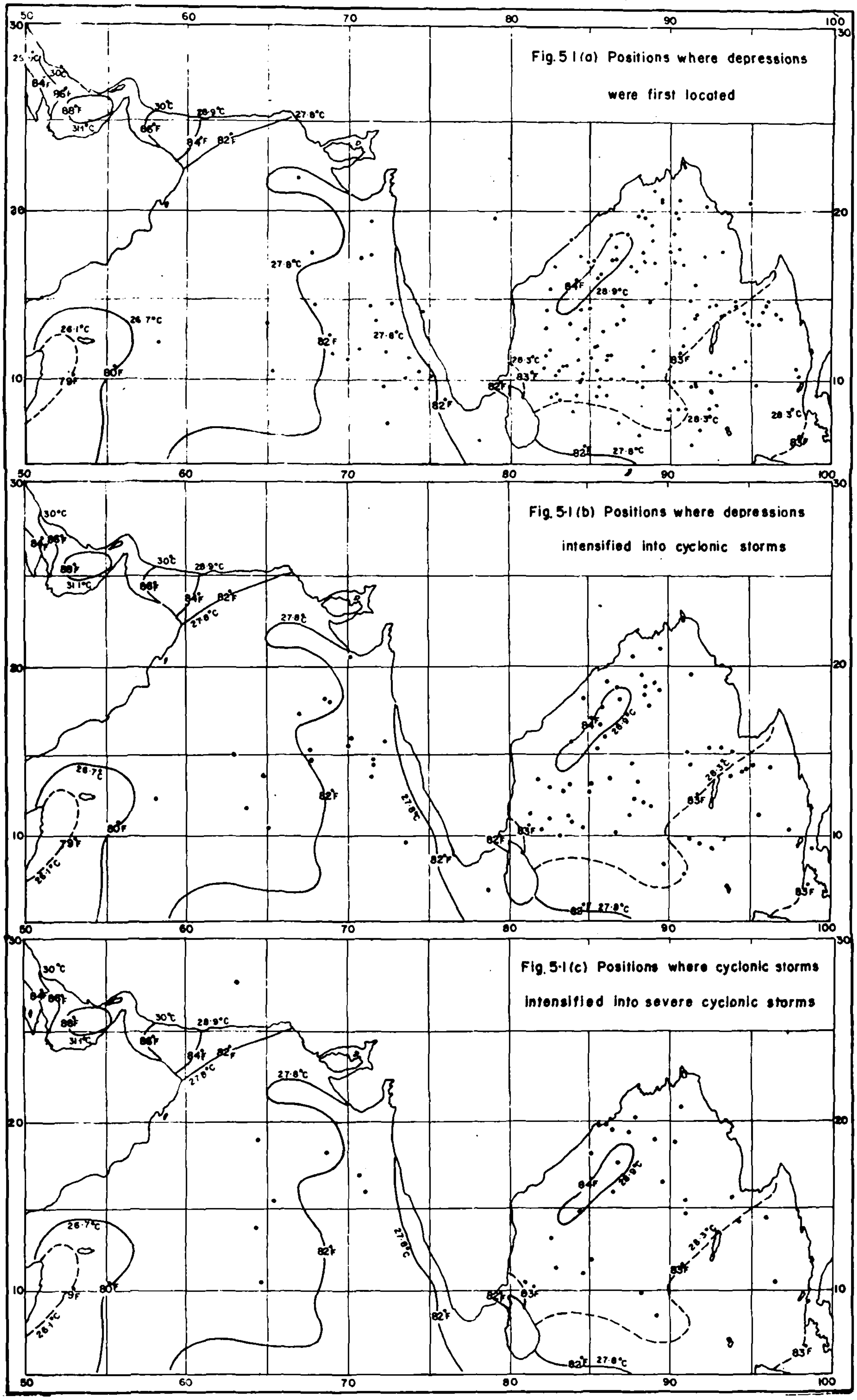



Fig. 5·1(a) Positions where depressions were first located

Fig. 5·1(b) Positions where depressions intensified into cyclonic storms

Fig. 5·1(c) Positions where cyclonic storms intensified into severe cyclonic storms

Mean Sea Surface Isotherms reproduced from "Monthly Charts of Mean, Minimum and Maximum sea surface temperature of the Indian Ocean", Special Publication, SP—99, 1967 (reprinted 1968) published by U.S. Naval Oceanographic Office, Washington D.C.

# NOVEMBER (1891-1970)

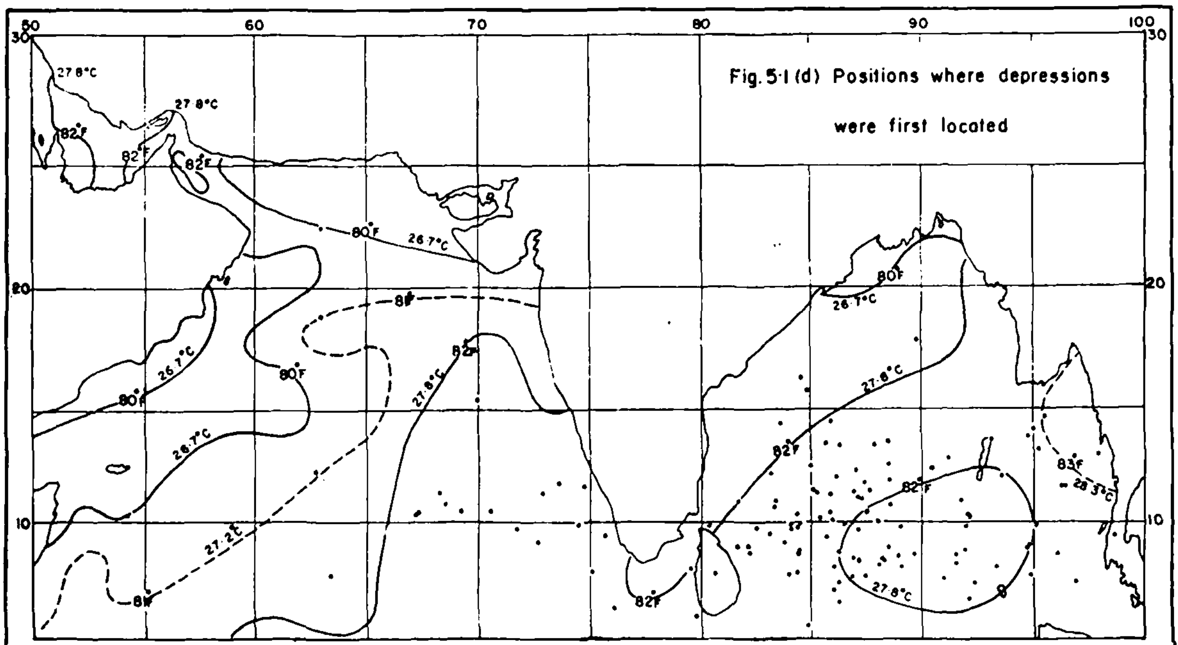



Fig. 5·1 (d) Positions where depressions were first located

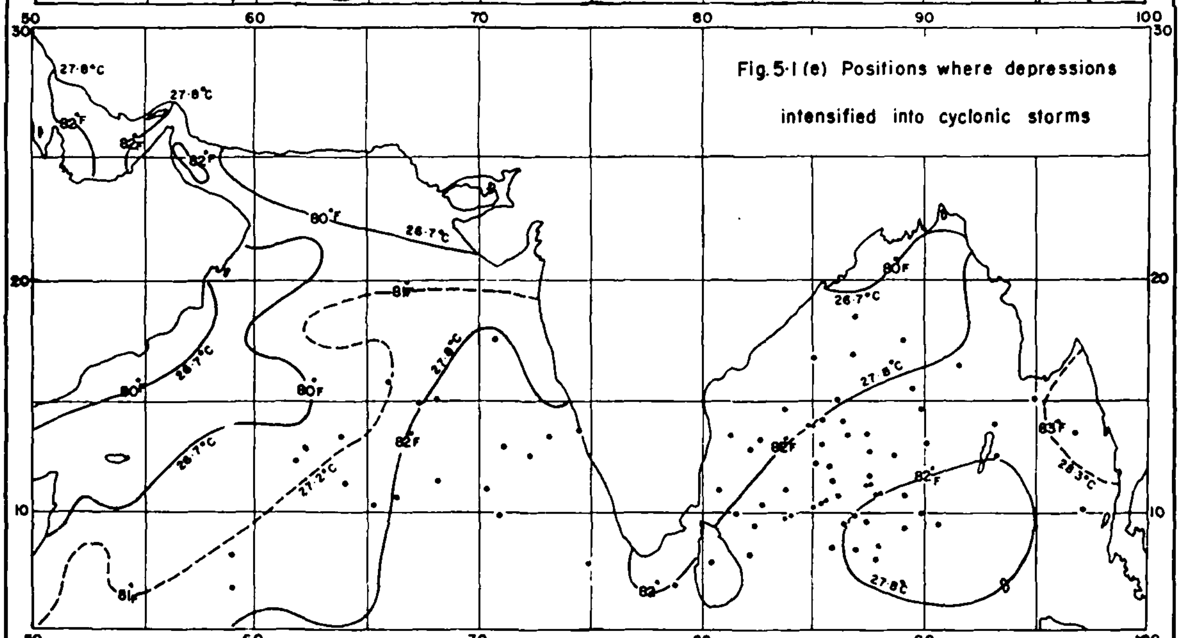



Fig. 5·1 (e) Positions where depressions intensified into cyclonic storms

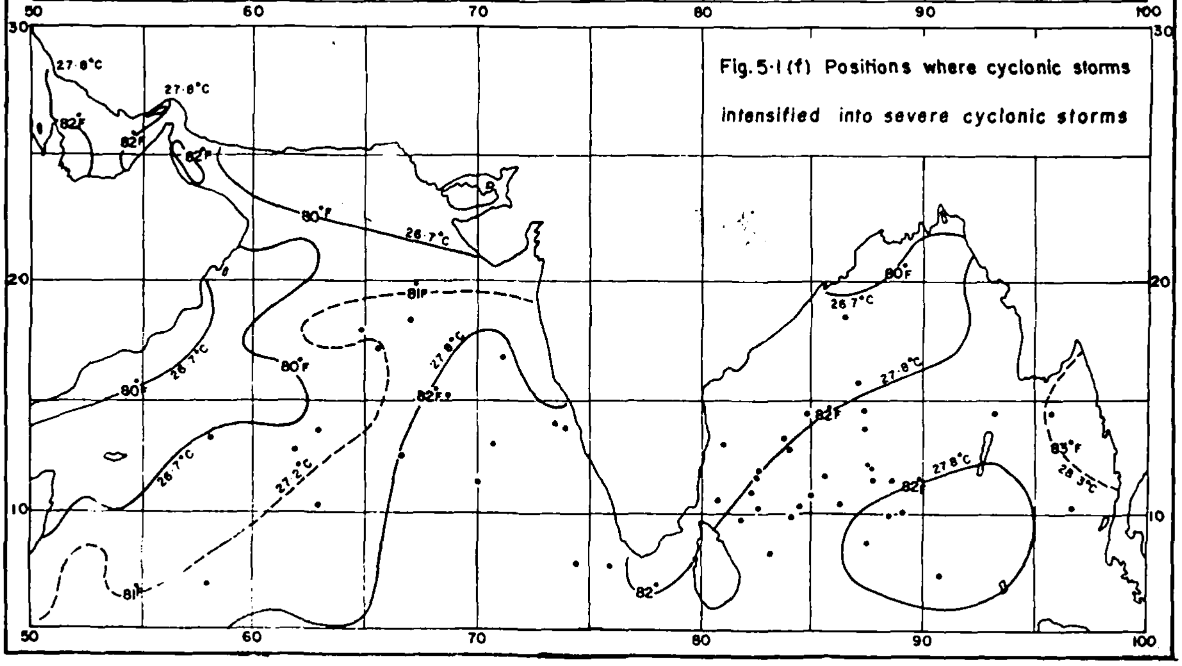



Fig. 5·1 (f) Positions where cyclonic storms intensified into severe cyclonic storms

Mean Sea Surface Isotherms reproduced from "Monthly Charts of Mean, Minimum and Maximum sea surface temperature of the Indian Ocean", Special Publication, SP—99, 1967 (reprinted 1968) published by U.S. Naval Oceanographic Office, Washington D.C.

# DECEMBER (1891 - 1970)

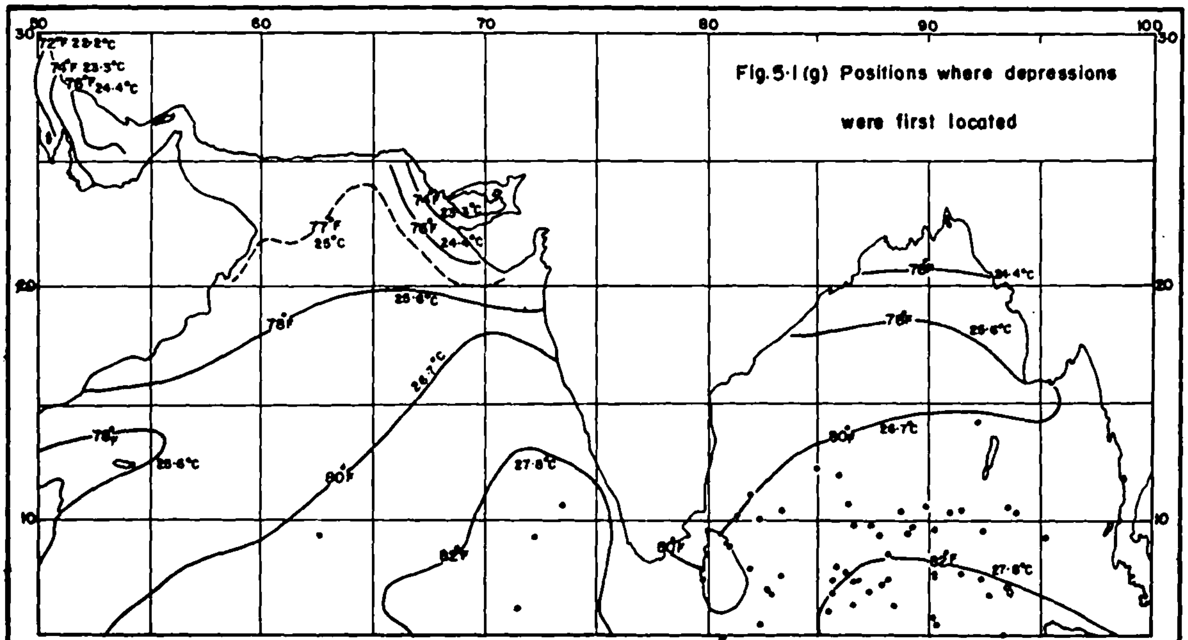


Fig. 5·1 (g) Positions where depressions were first located

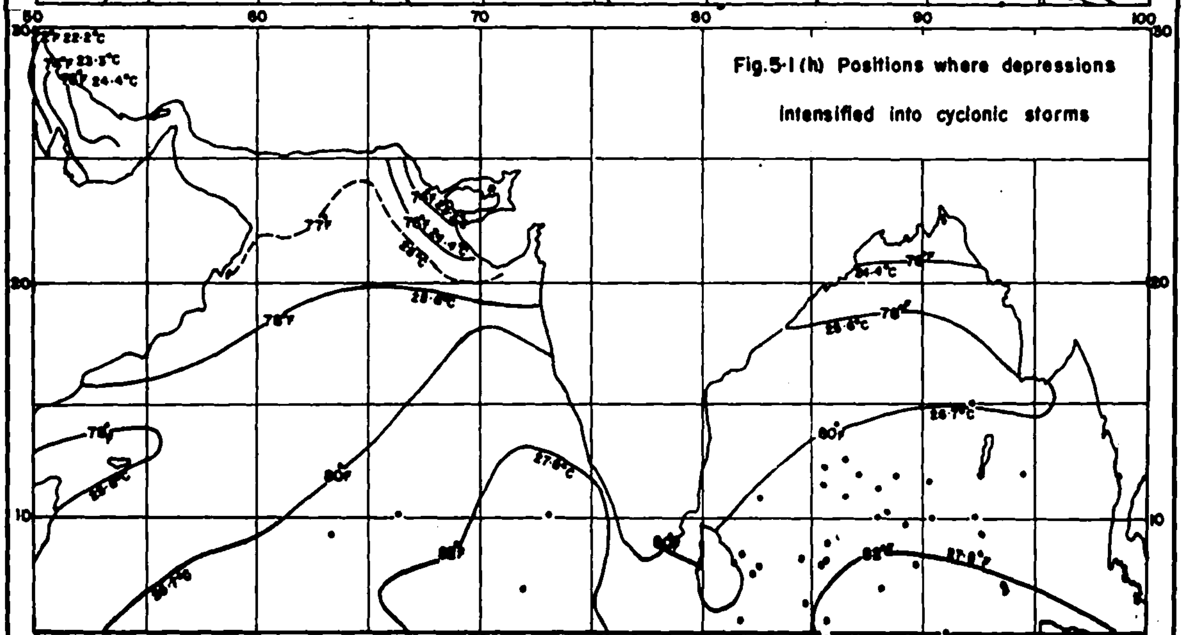


Fig. 5·1 (h) Positions where depressions intensified into cyclonic storms

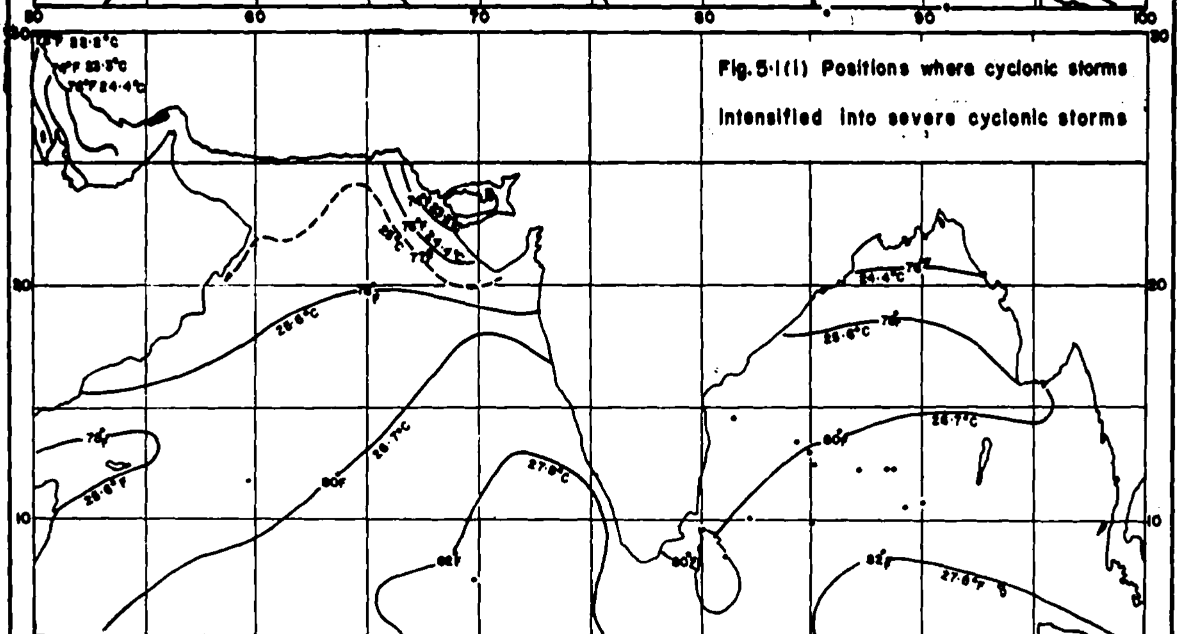


Fig. 5·1 (i) Positions where cyclonic storms intensified into severe cyclonic storms

Mean Sea Surface Isotherms reproduced from "Monthly Charts of Mean, Minimum and Maximum sea surface temperature of the Indian Ocean", Special Publication, SP—99, 1967 (reprinted 1968) published by U. S. Naval Oceanographic Office, Washington D. C.

FIG. 5·2 (a) POSITIONS WHERE DEPRESSIONS WERE FIRST LOCATED (1-15 OCT.) (1891-1970)

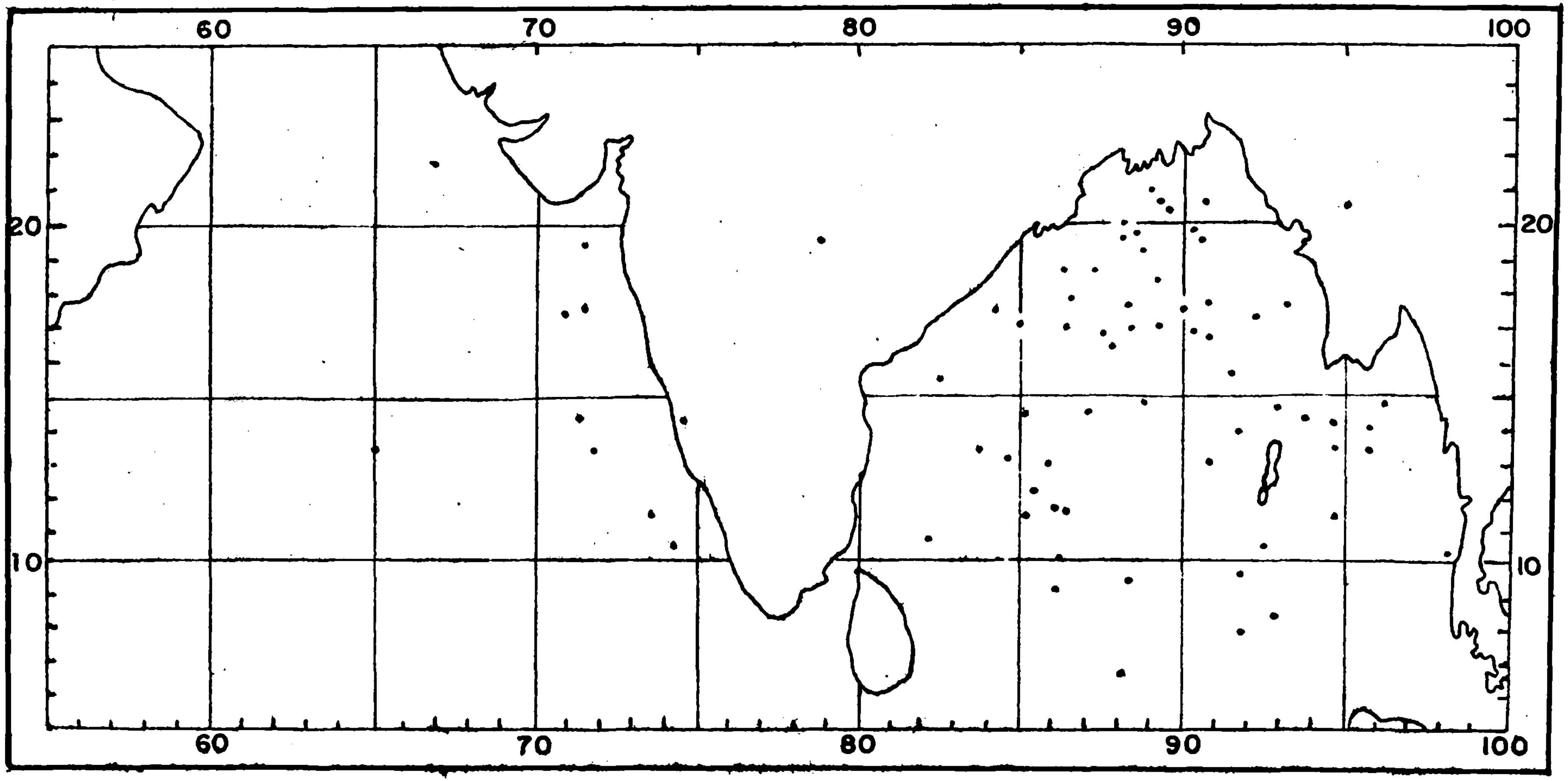


FIG. 5·2 (b) POSITIONS WHERE DEPRESSIONS WERE FIRST LOCATED (16-31 OCT.) (1891-1970)

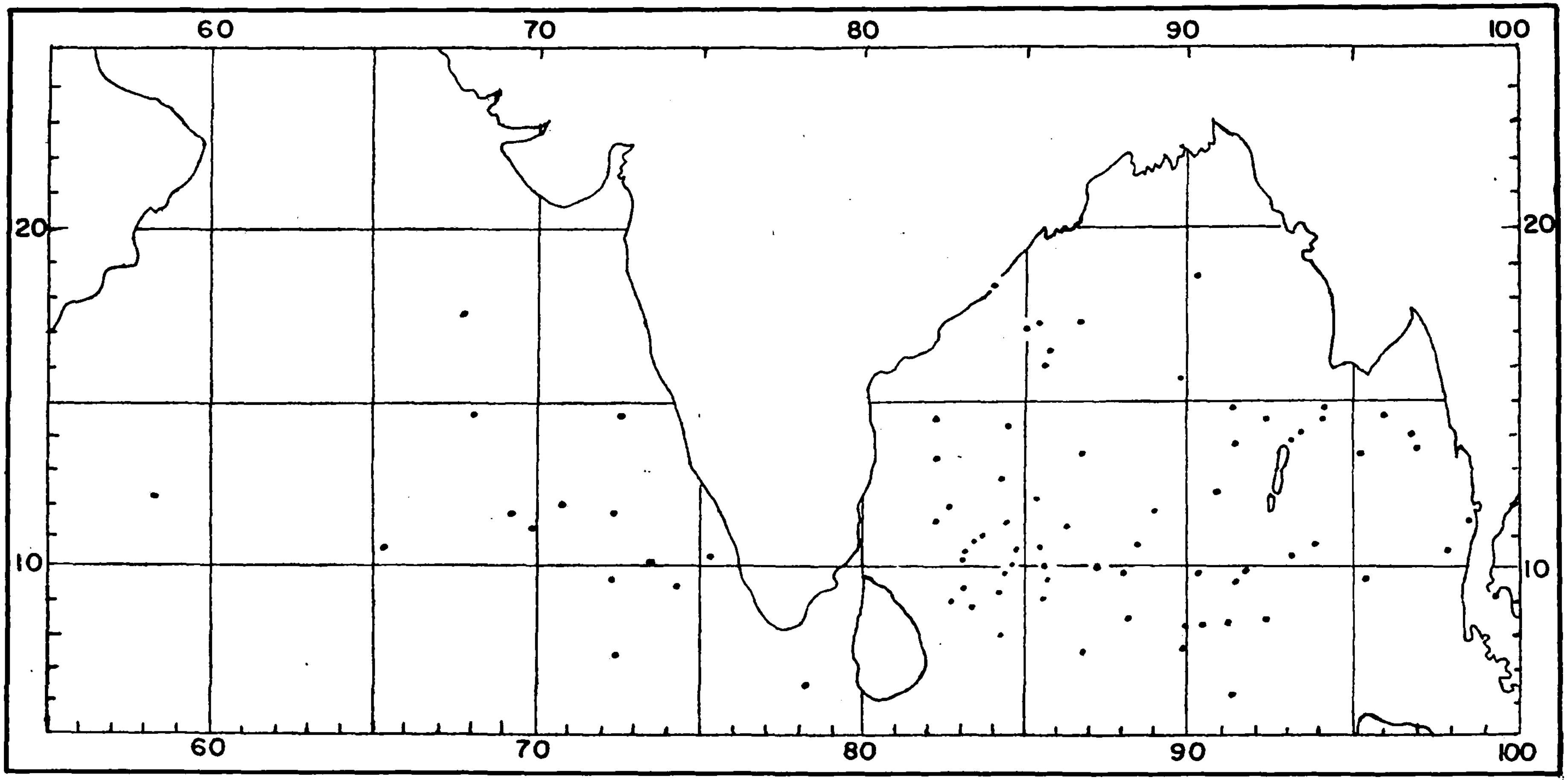
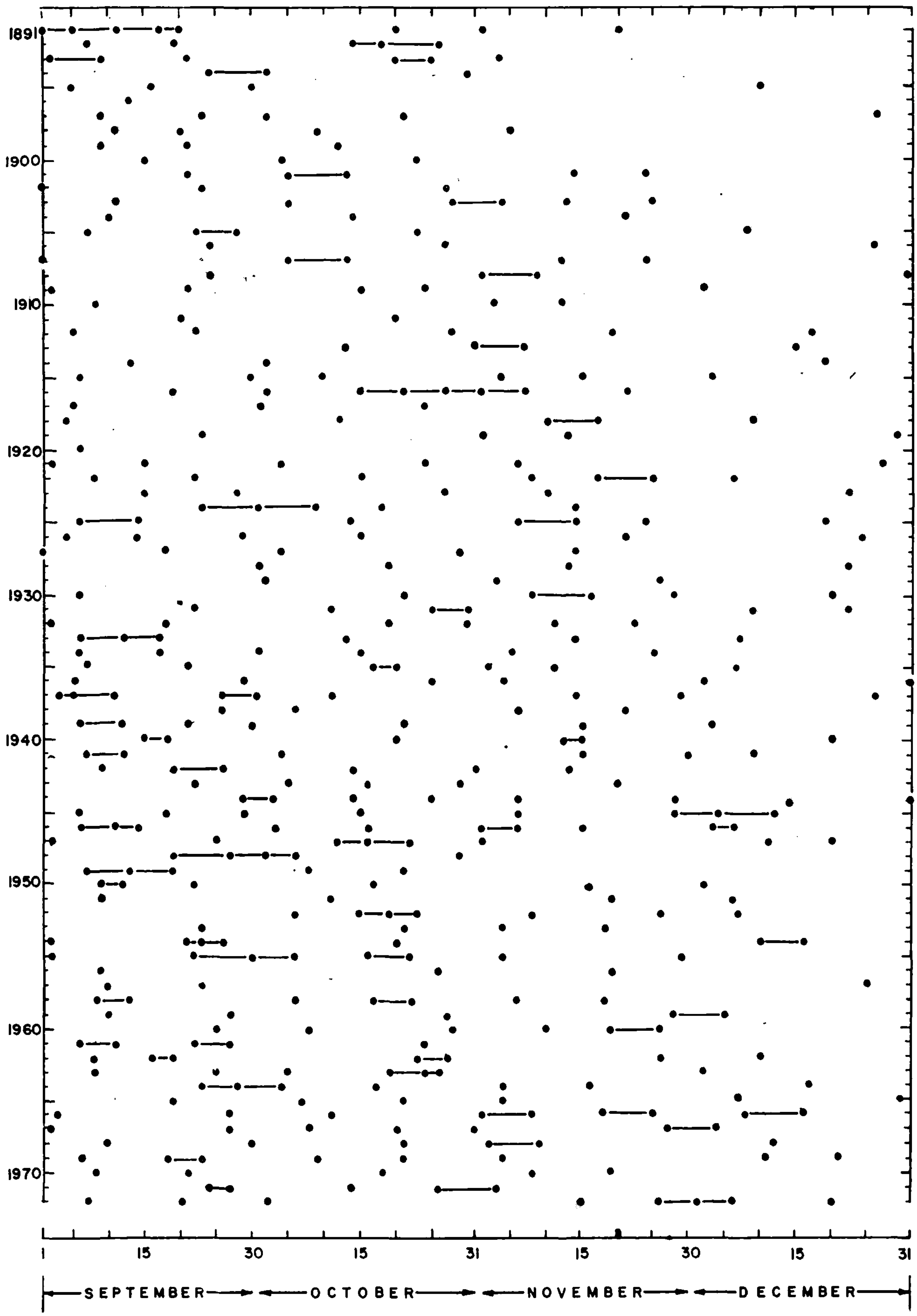
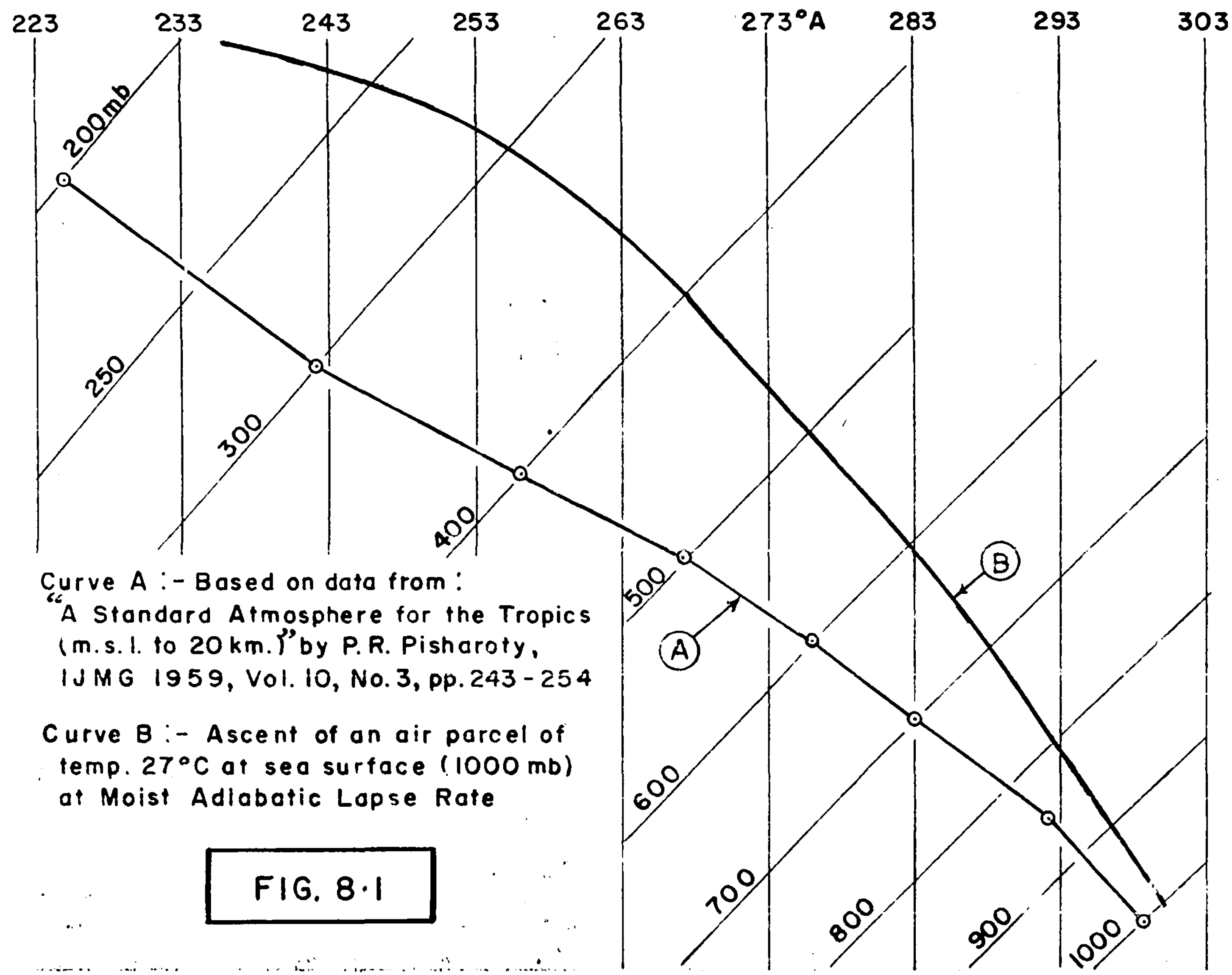


FIG. 5·3 STORM CLUSTERS – BAY OF BENGAL (1891-1972)




EACH DOT REPRESENTS THE INITIAL DATE OF FORMATION OF THE DISTURBANCE (DEPRESSION/STORM).
DISTURBANCES FORMING A CLUSTER ARE JOINED BY A STRAIGHT LINE.

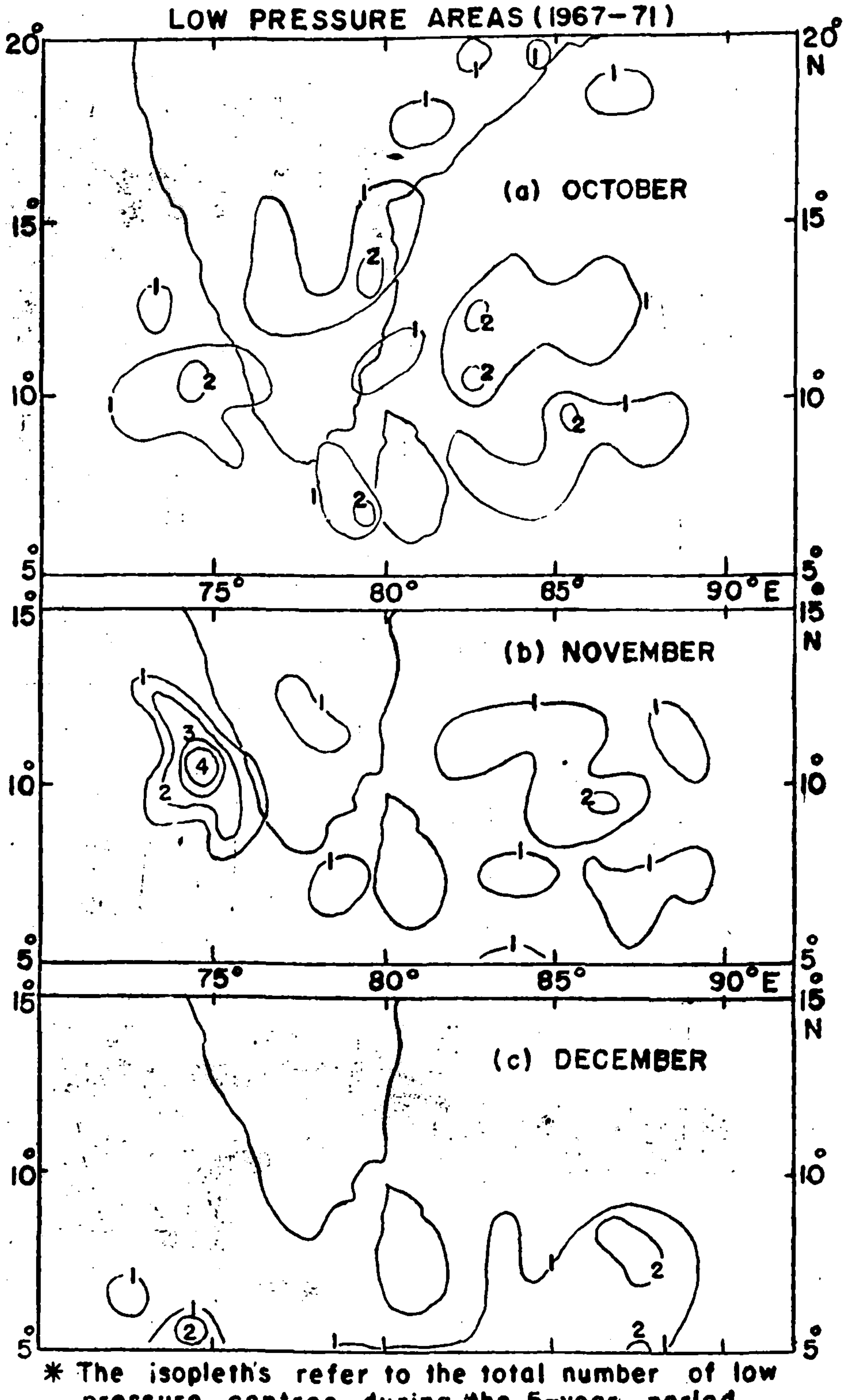



Curve A :- Based on data from :
"A Standard Atmosphere for the Tropics (m.s.l. to 20 km.)" by P.R. Pisharoty, IJMG 1959, Vol. 10, No. 3, pp. 243 - 254

Curve B :- Ascent of an air parcel of temp. 27°C at sea surface (1000 mb) at Moist Adiabatic Lapse Rate

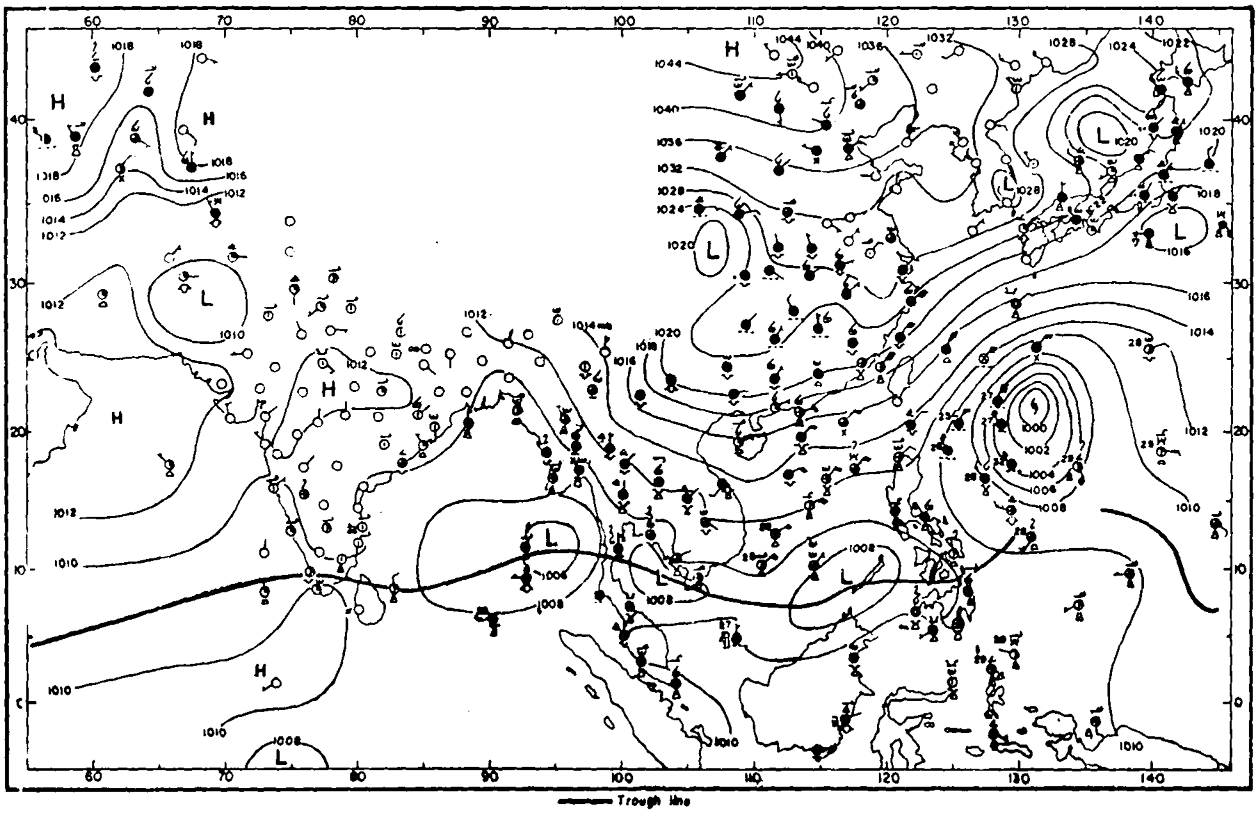
FIG. 8·1

FIG. 12·1 . SPATIAL DISTRIBUTION OF CENTRES* OF LOW PRESSURE AREAS (1967–71)




* The isopleth's refer to the total number of low pressure centres during the 5-year period (1967–71)

FIG. 15·1 SURFACE CHART 0000 GMT 3 NOV. 69




# FIG. 15·2 0300 GMT 3 NOV. 69

ESSA-8 ORBIT 4049,4048 DATE 3 NOV. 69

(0553,0353 GMT)

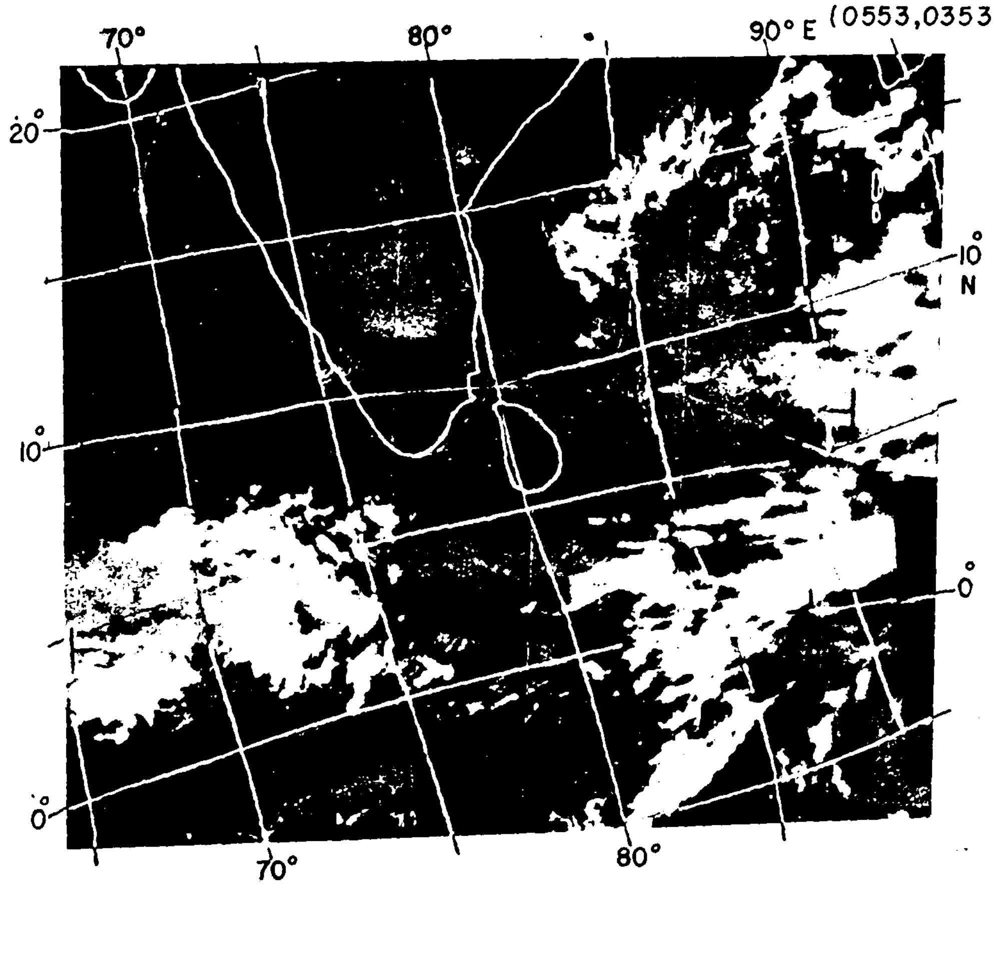


FIG. 15·3 SYNOPTIC CHARTS 0300 GMT 4 NOV. 69

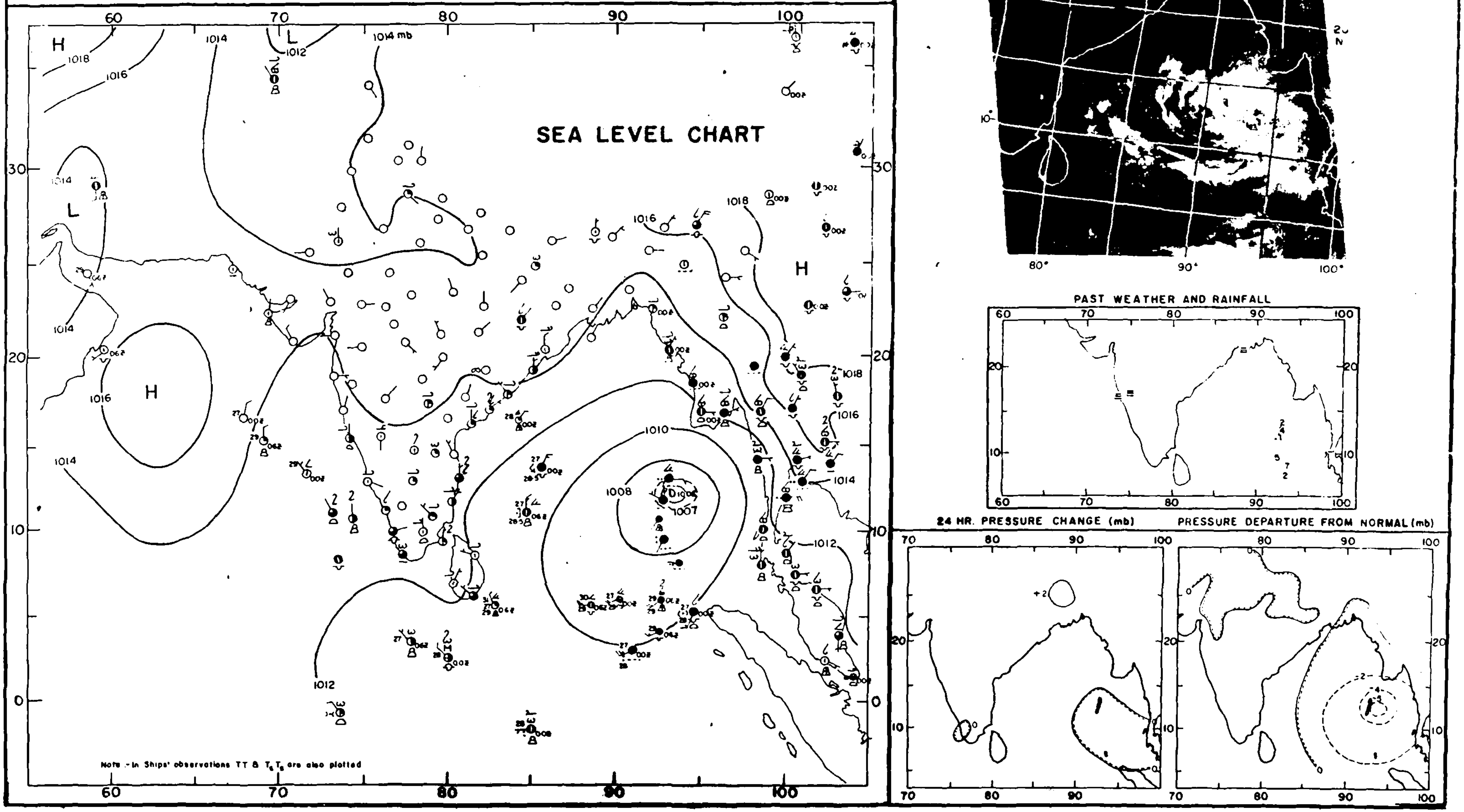
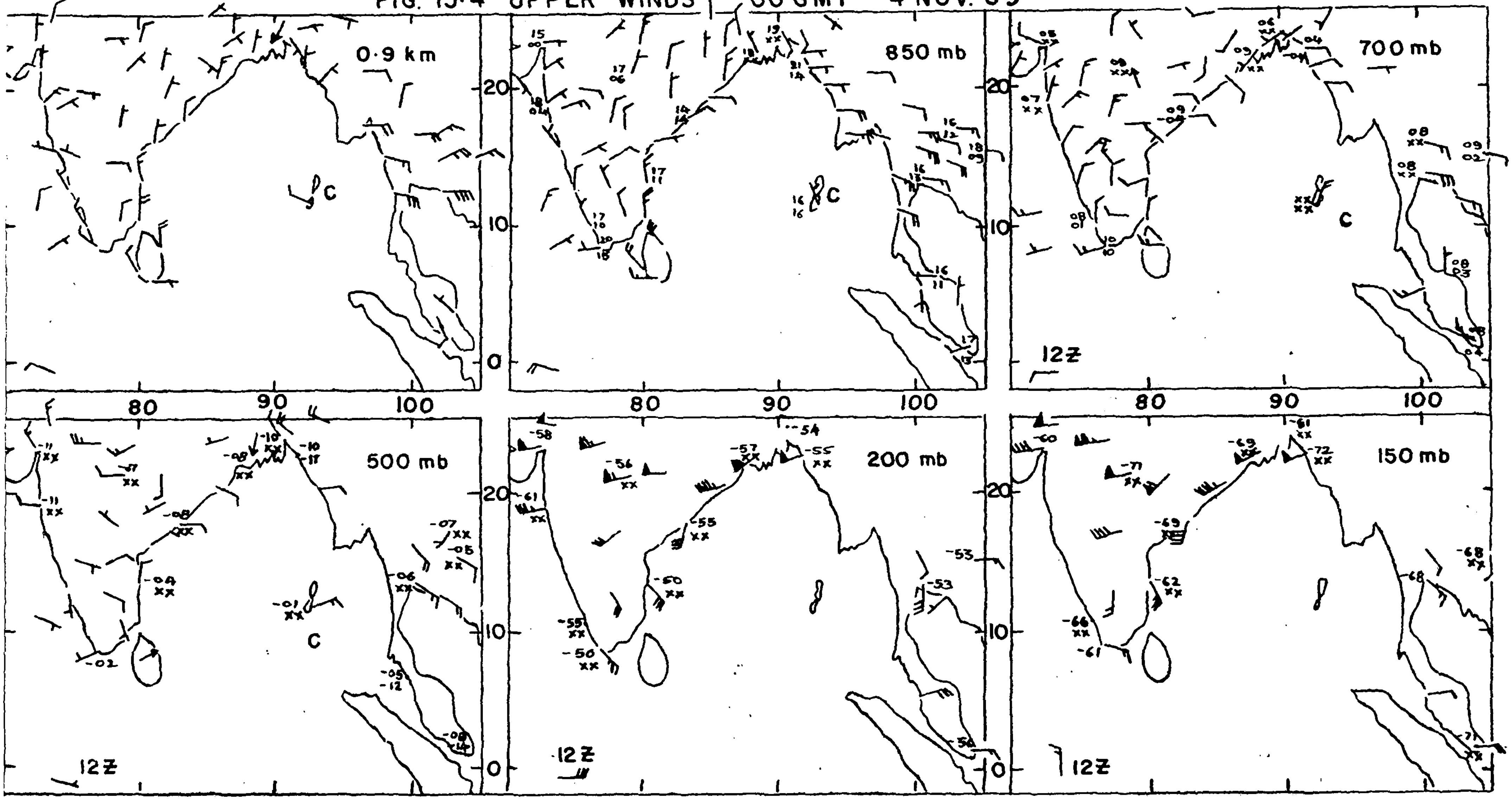


FIG. 15·4 UPPER WINDS 00 GMT 4 NOV. 69




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

# FIG. 15·5 SYNOPTIC CHARTS 1200 GMT 4 NOV. 69

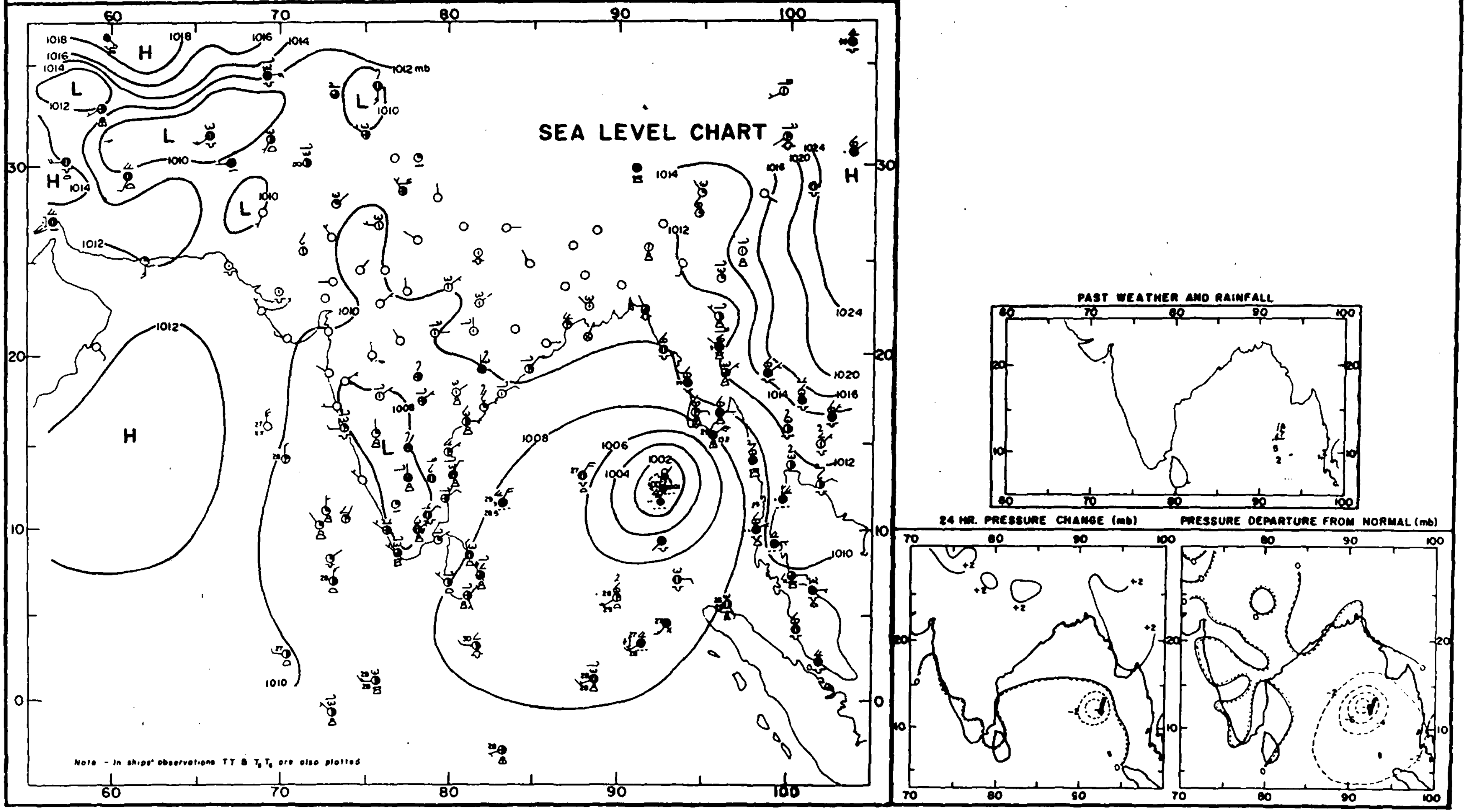
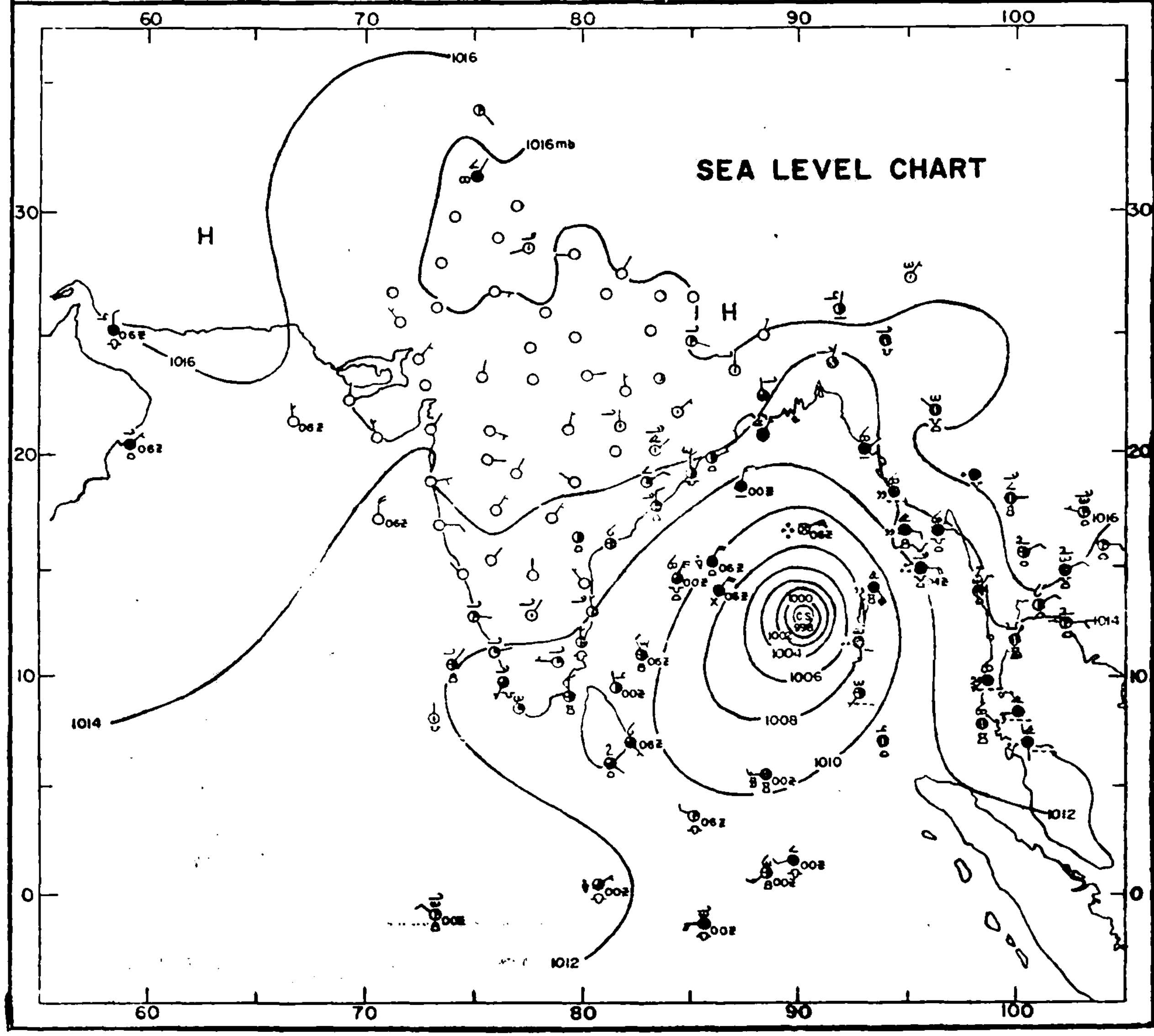
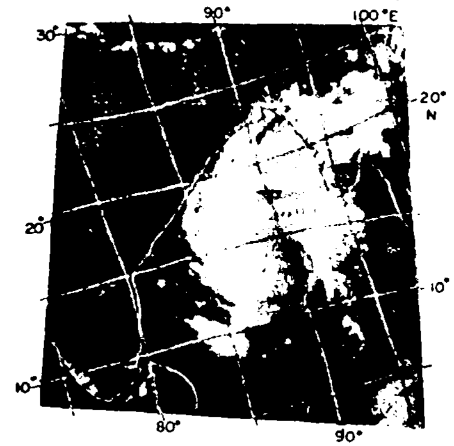
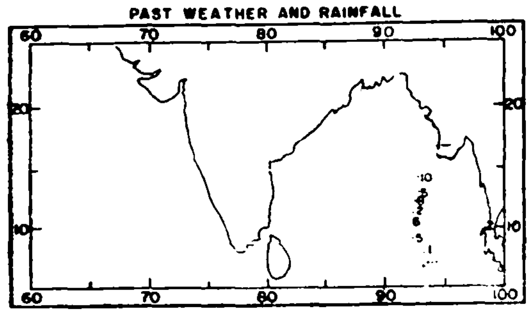
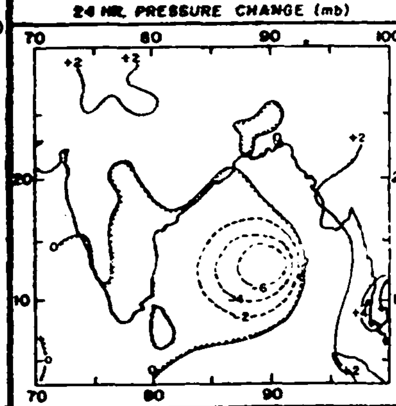


FIG. 15·6 SYNOPTIC CHARTS 0300 GMT 5 NOV. 69



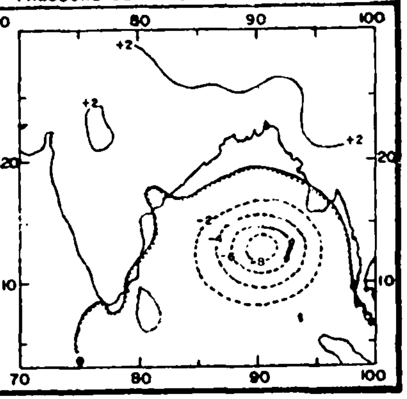
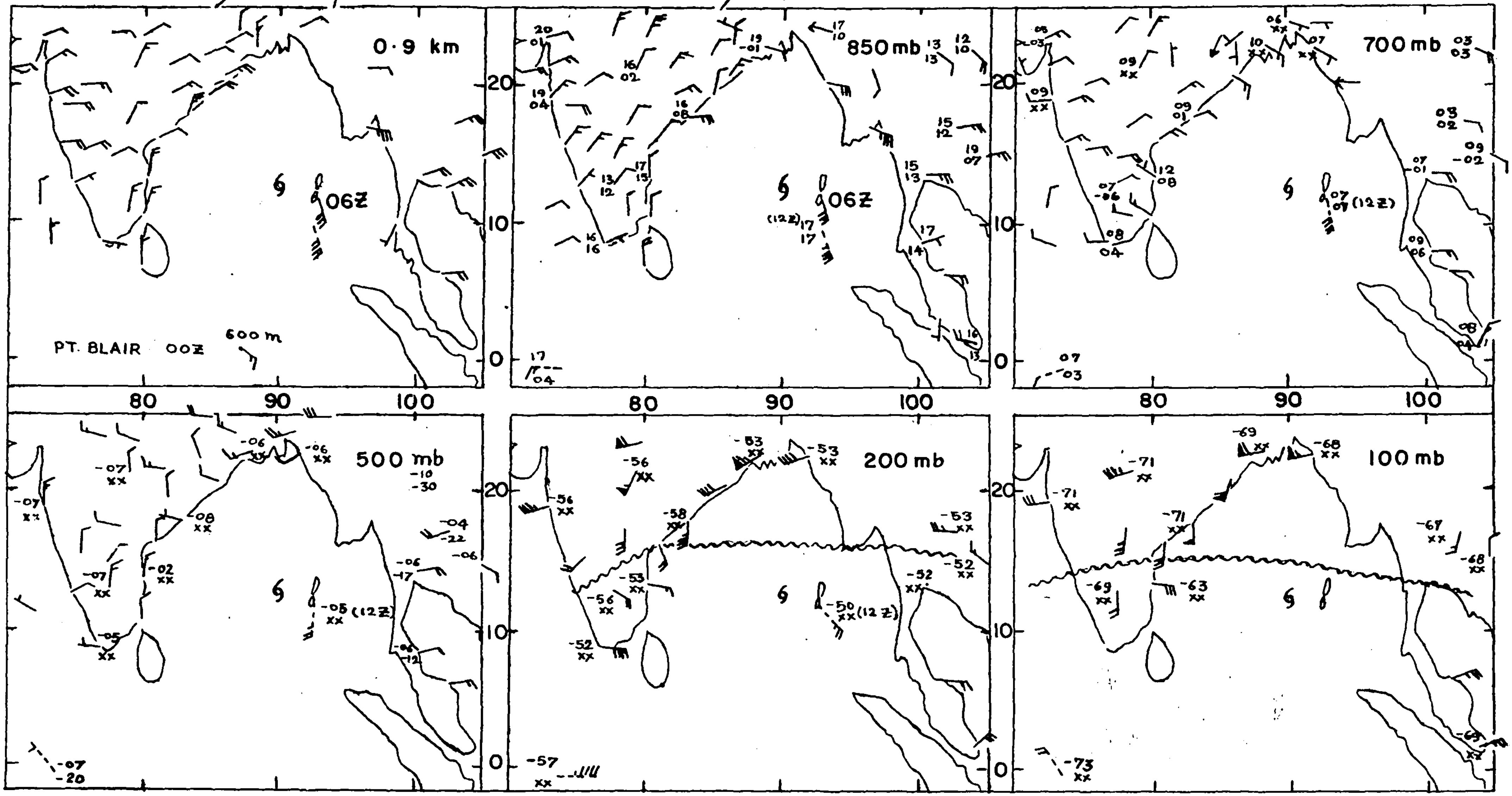



FIG. 15·7 UPPER WINDS 00 GMT 5 NOV. 69




Ridge line — Cyclonic storm — Plotted figures TT & $T_dT_d$ — Broken shaft indicates 12 Z data.

FIG. 15·8 SYNOPTIC CHARTS 0300 GMT 6 NOV. 69

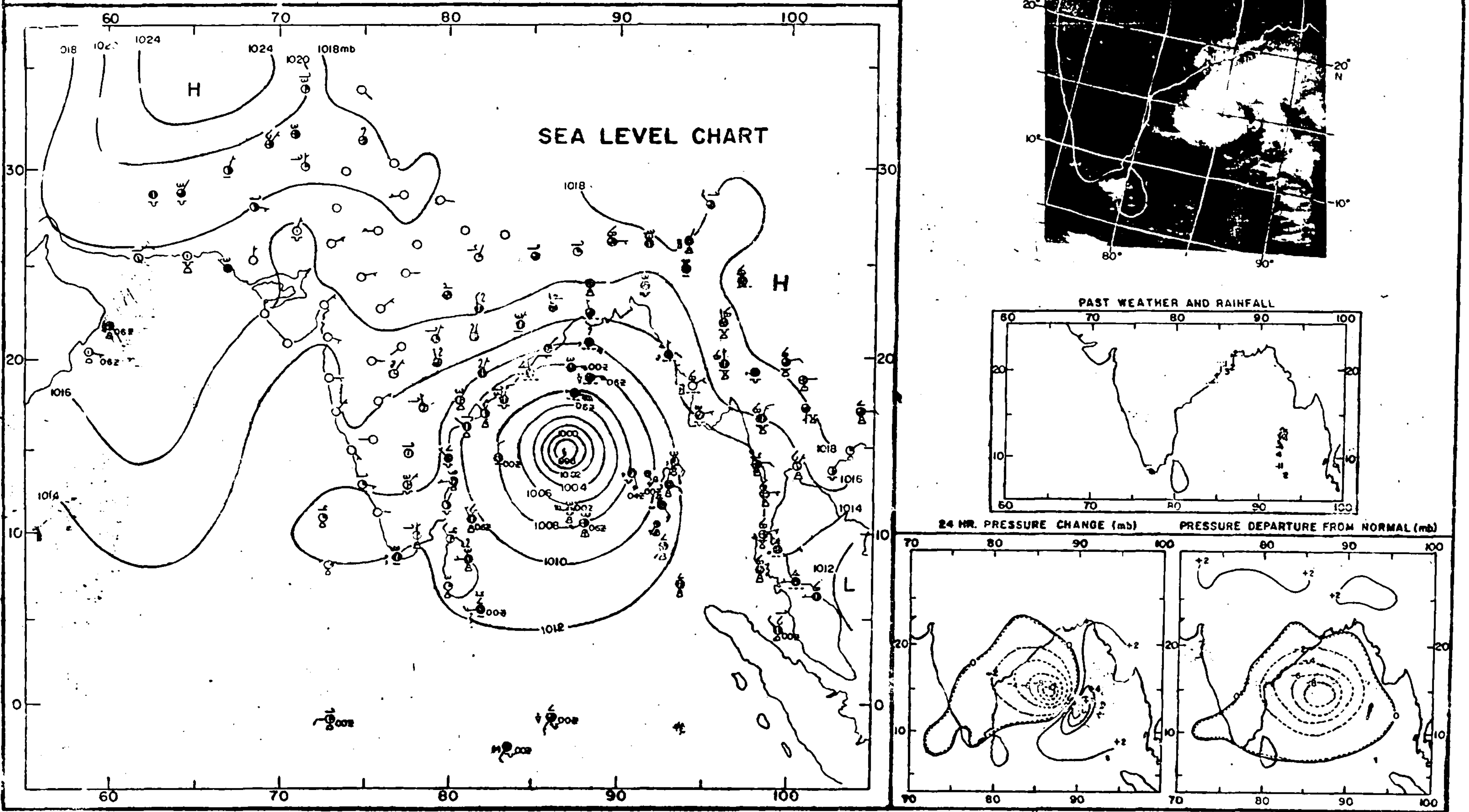
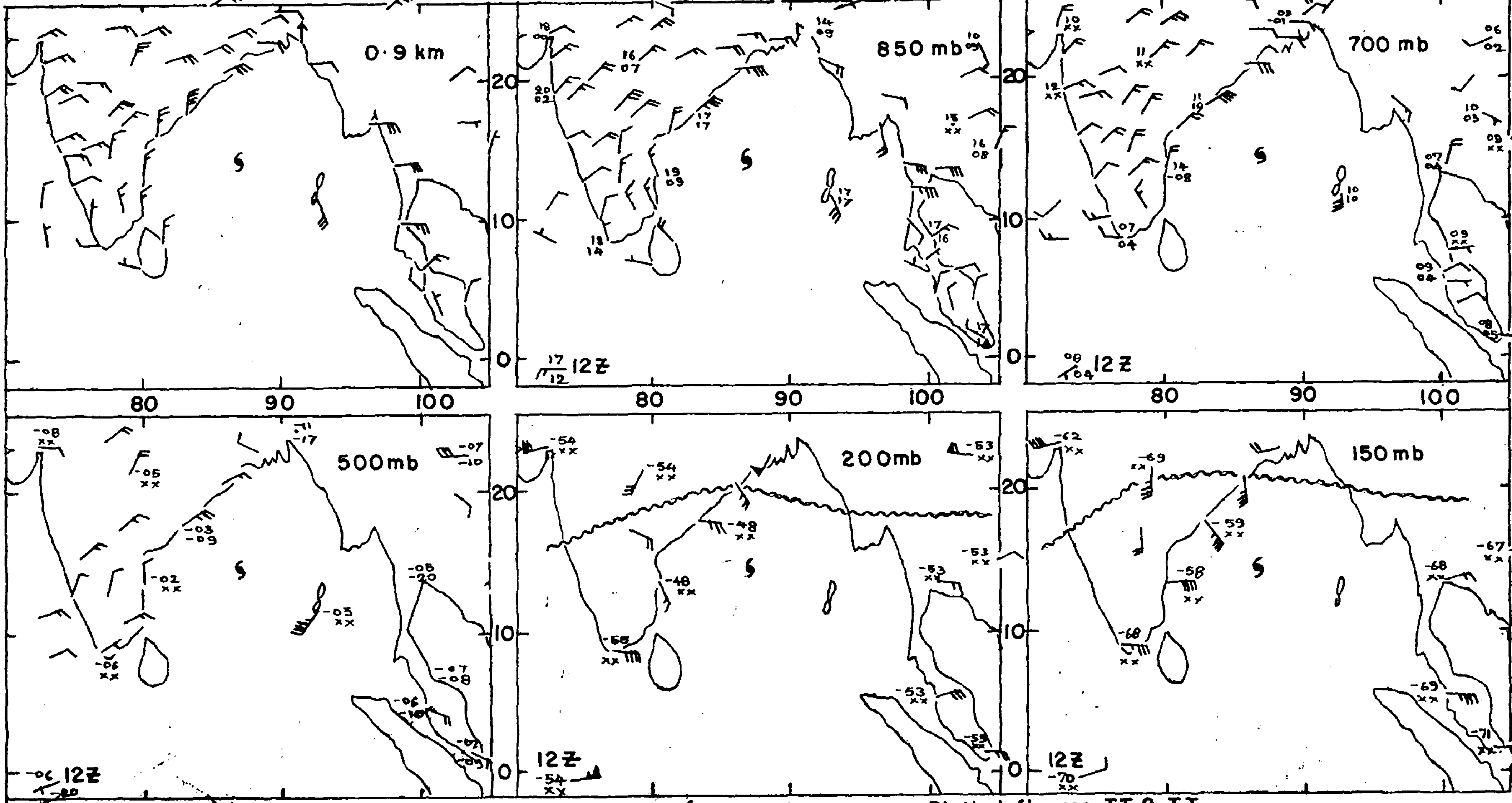
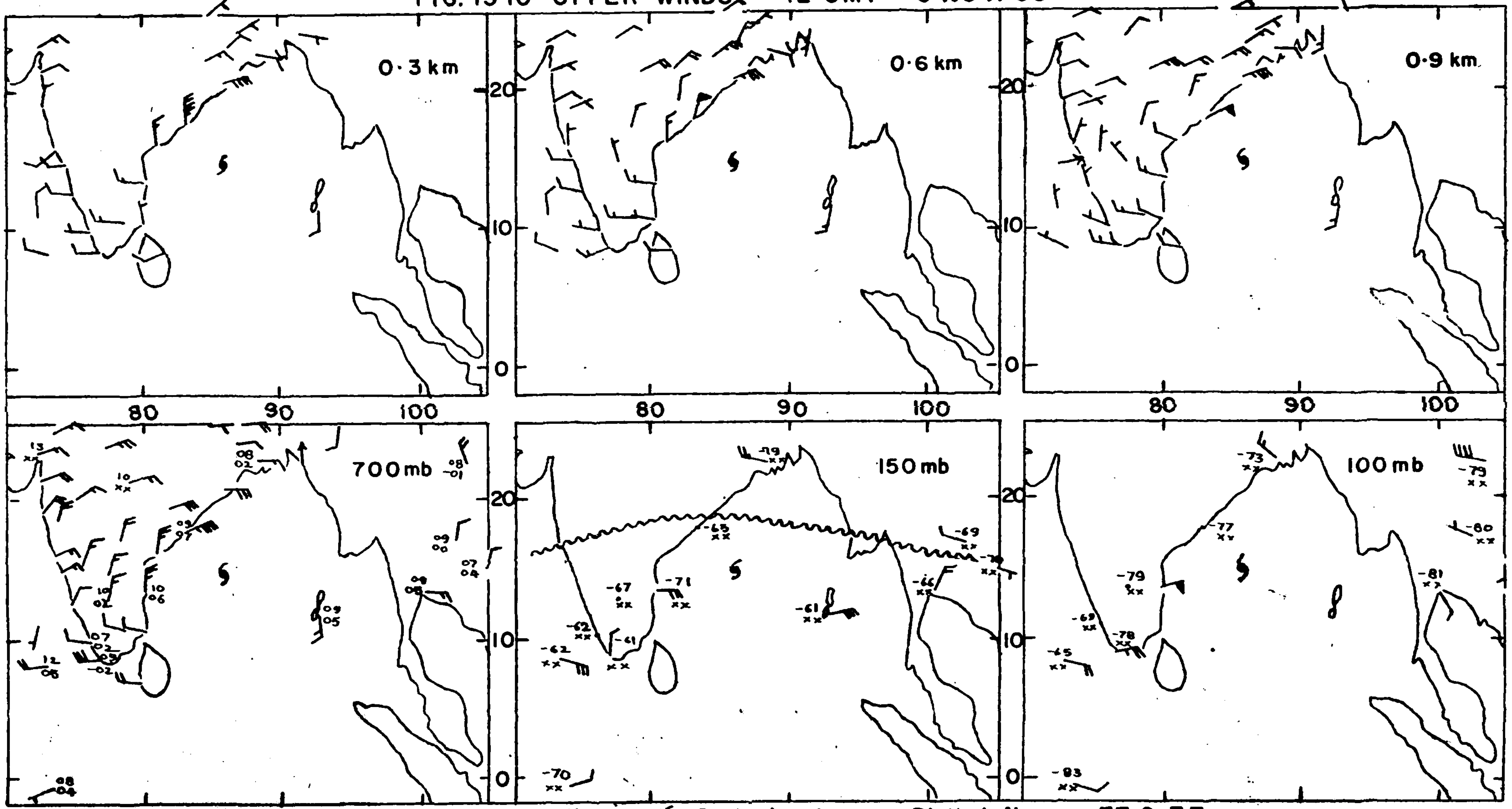


FIG. 15·9 UPPER WINDS 00 GMT 6 NOV. 69




Ridge line    Cyclonic storm    Plotted figures TT & $T_dT_d$

FIG. 15·10 UPPER WINDS 12 GMT 6 NOV. 69




Ridge line   Cyclonic storm   Plotted figures TT & $T_dT_d$

# FIG. 15·11 SYNOPTIC CHARTS 0300 GMT 7 NOV. 69

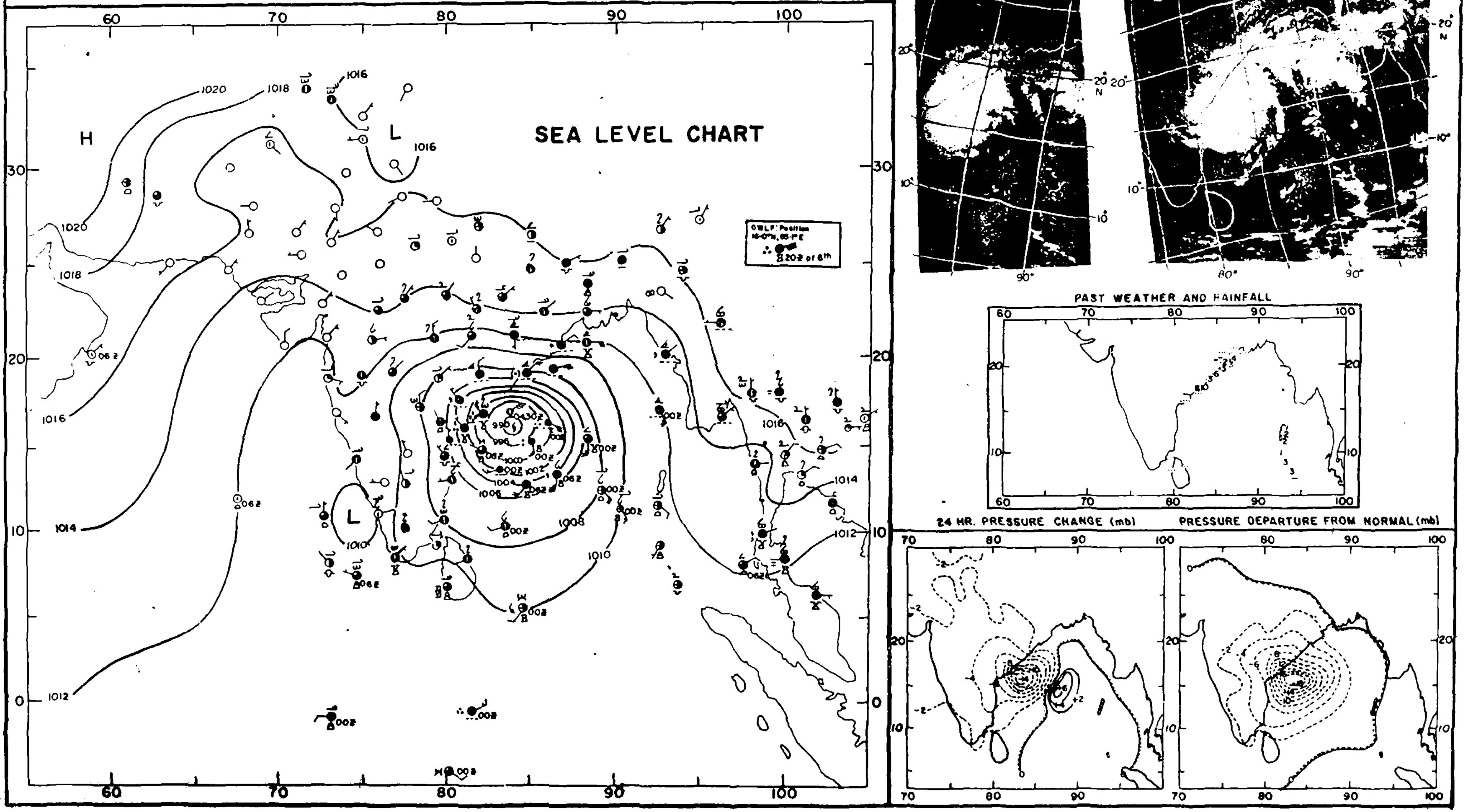
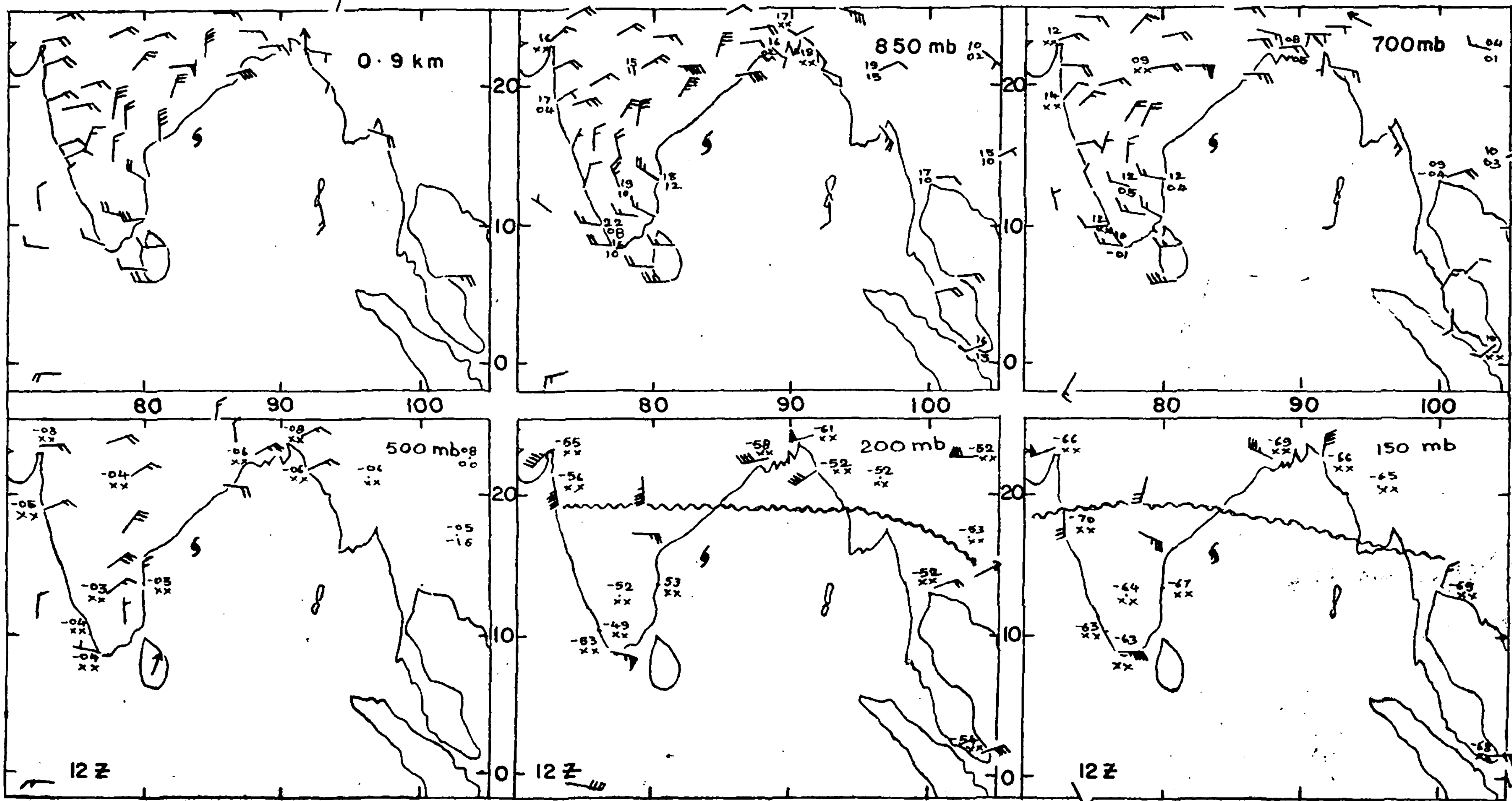


FIG. 15·12 UPPER WINDS 00 GMT 7 NOV. 69




Ridge line · Cyclonic storm · Plotted figures TT & $T_dT_d$

FIG. 15·13 SYNOPTIC CHARTS 1200 GMT 7 NOV. 69

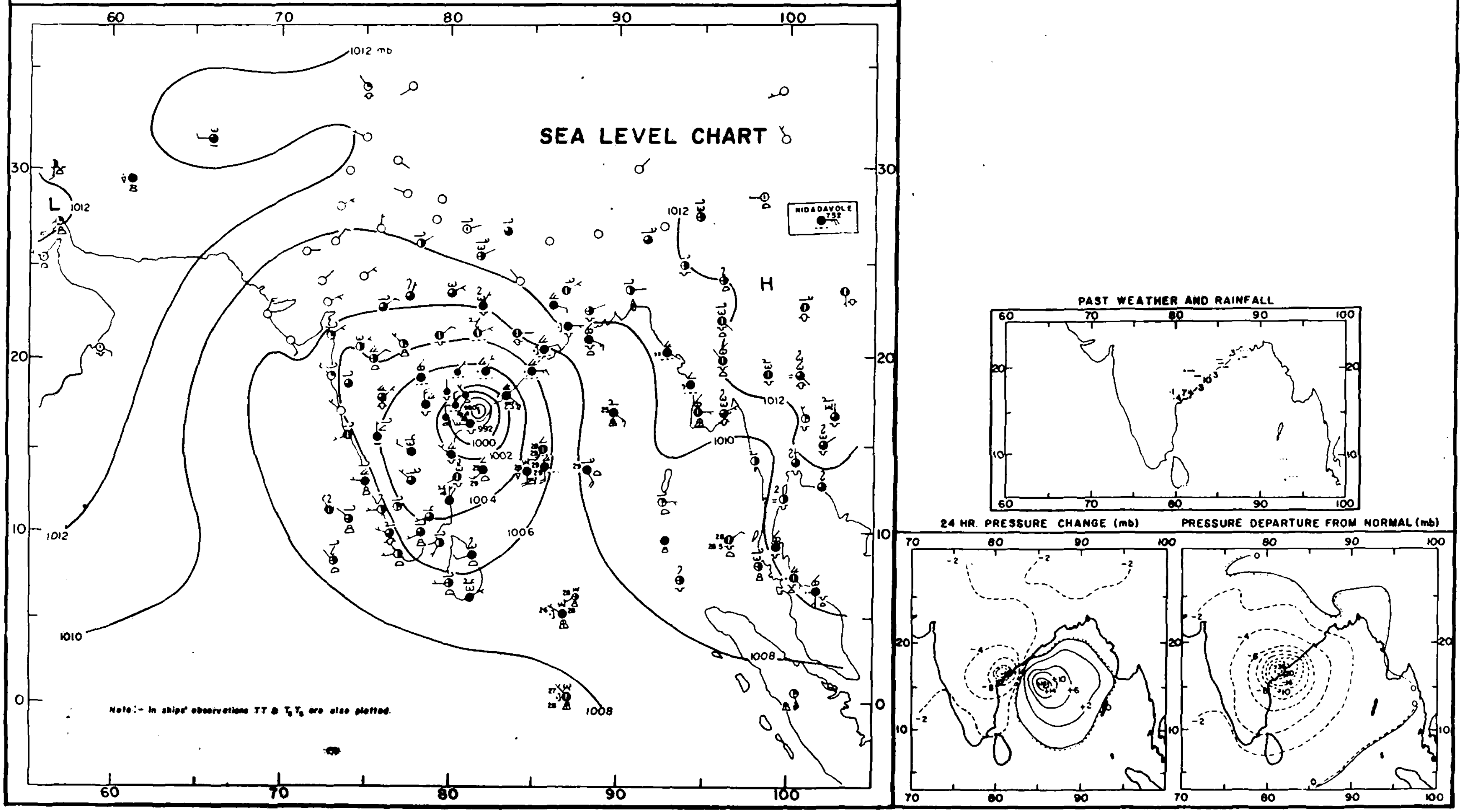


FIG. 15·14 SYNOPTIC CHARTS 0300 GMT 8 NOV. 69

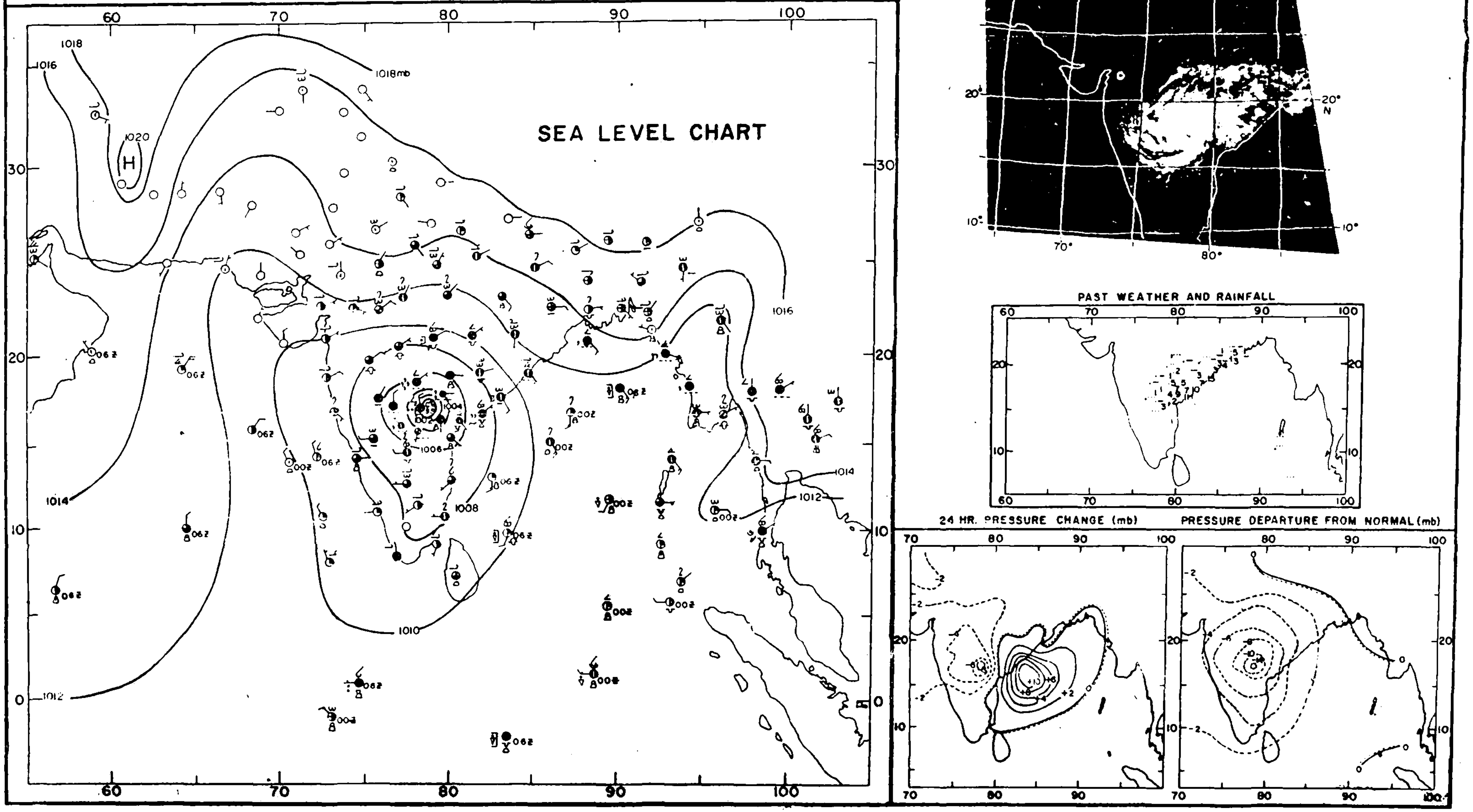
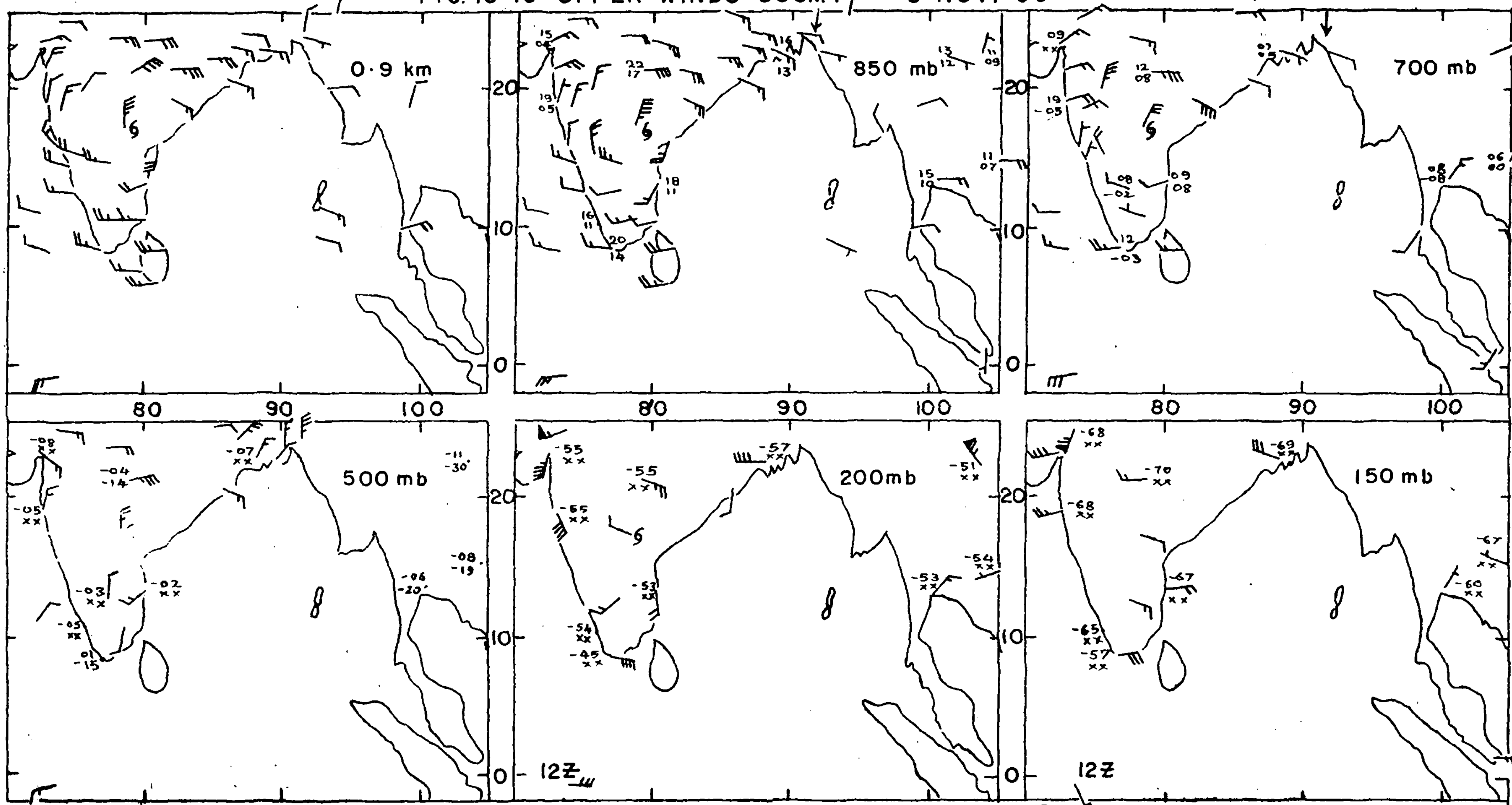
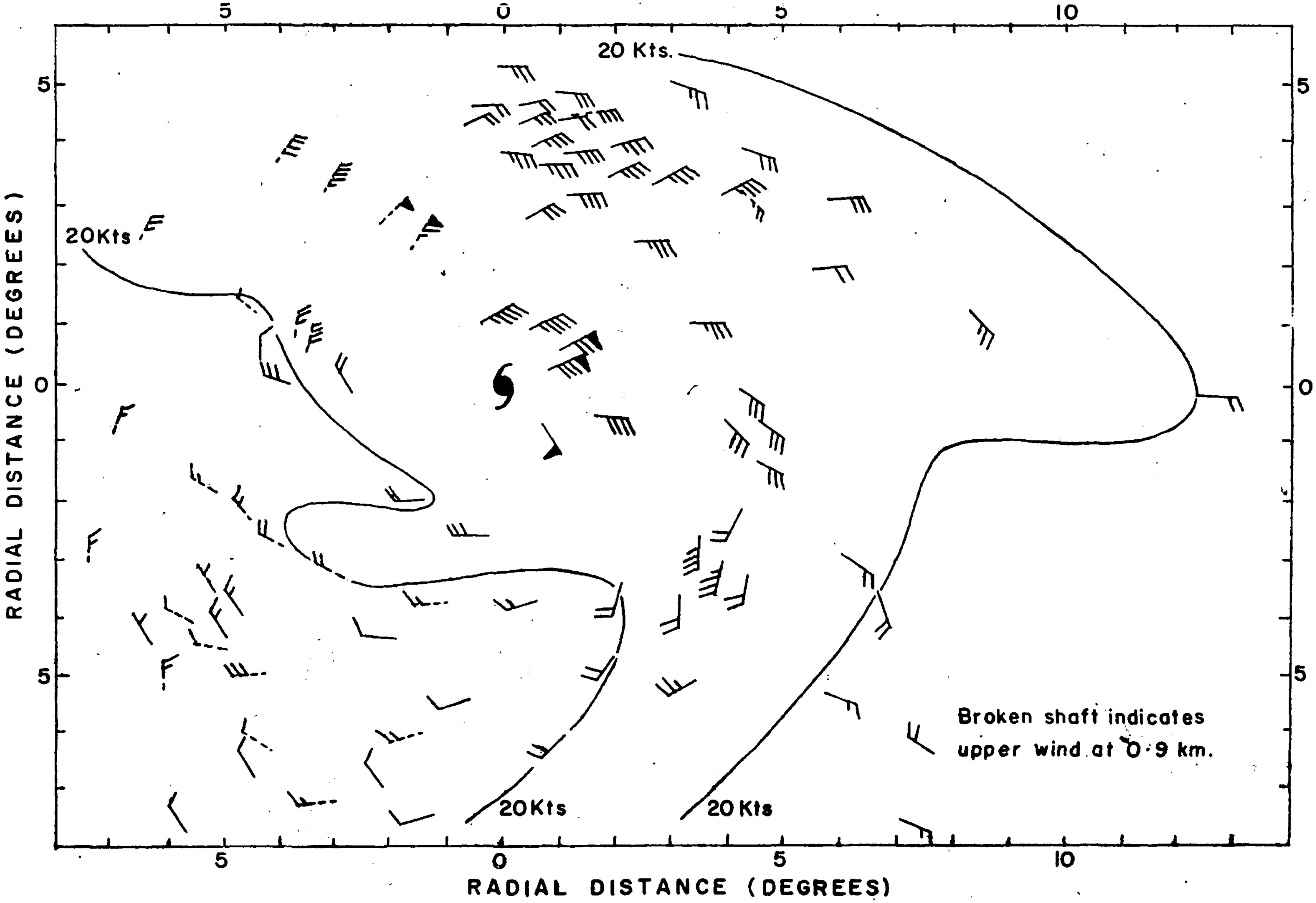


FIG. 15·15 UPPER WINDS OOGMT 8 NOV. 69




ɕ Cyclonic storm Plotted figures TT 8 $T_dT_d$

FIG. 15·16 COMPOSITE WIND CHART (0000 GMT OF 6 NOV. 69 TO 1200 GMT OF 7 NOV. 69)



# FIG. 16·1 SYNOPTIC CHARTS 0300 GMT 2 NOV. 71

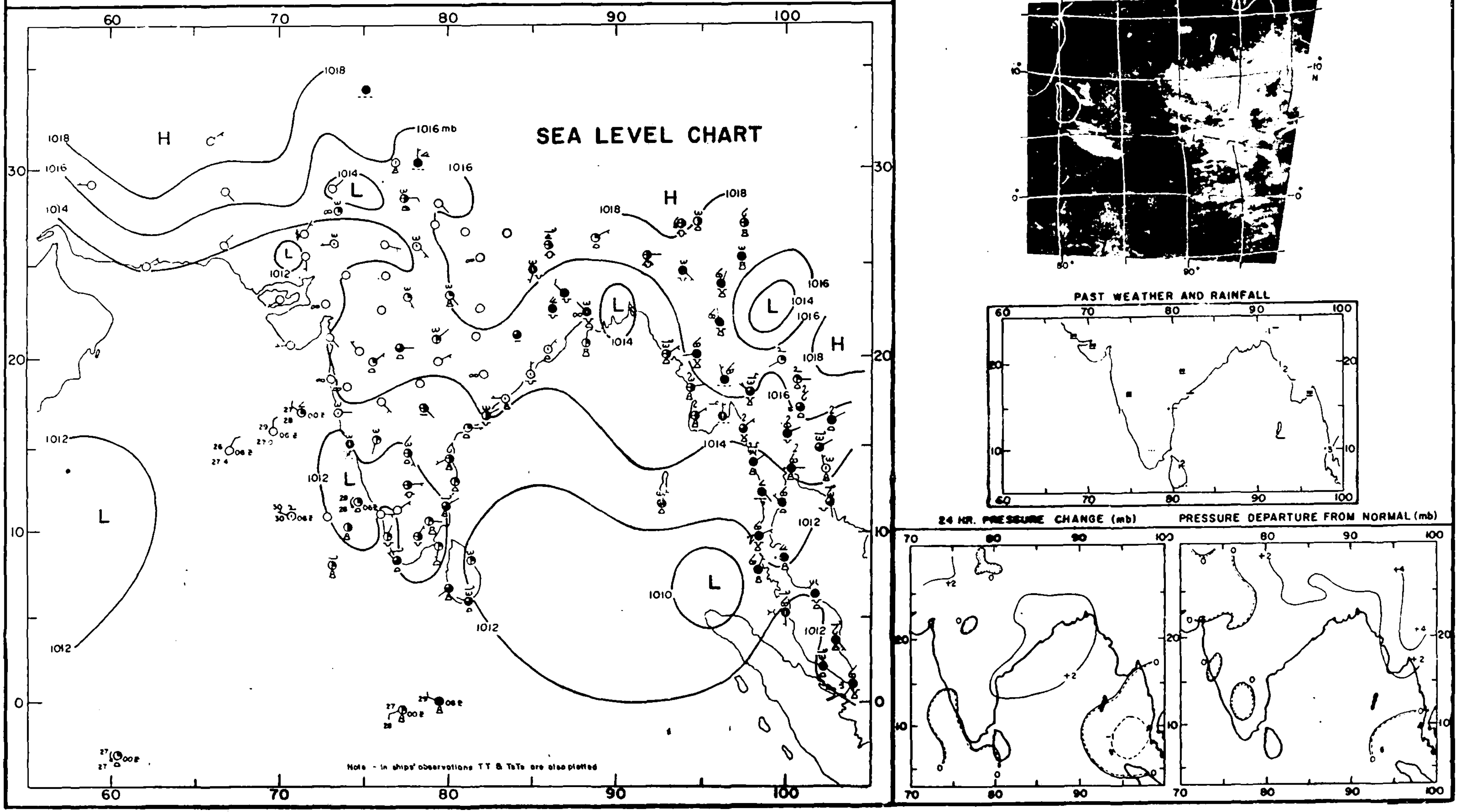
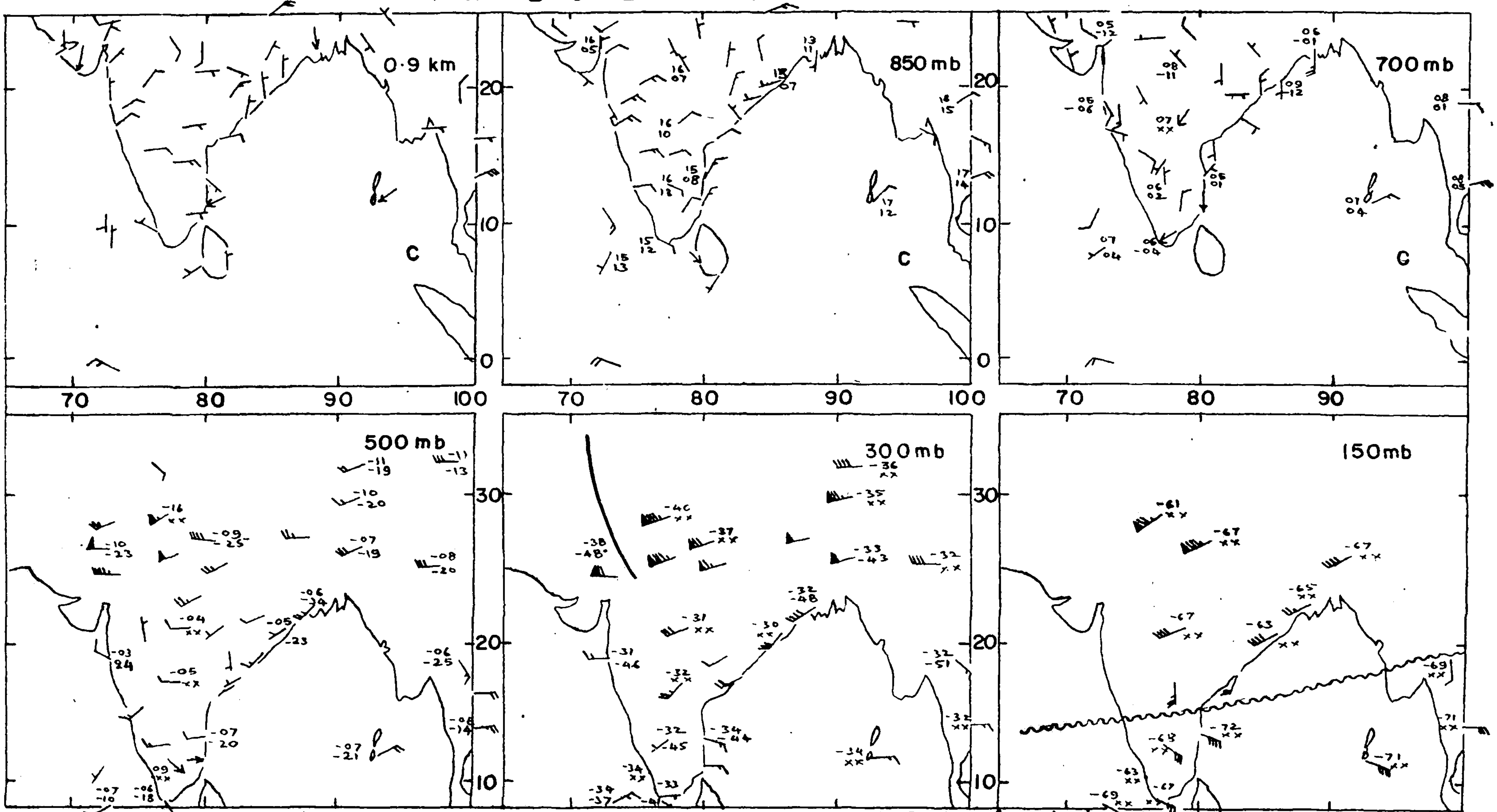


FIG. 16·2 UPPER WINDS 00GMT 2NOV. 71




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

FIG. 16·3 SURFACE CHART 0000 GMT 3 NOV. 71

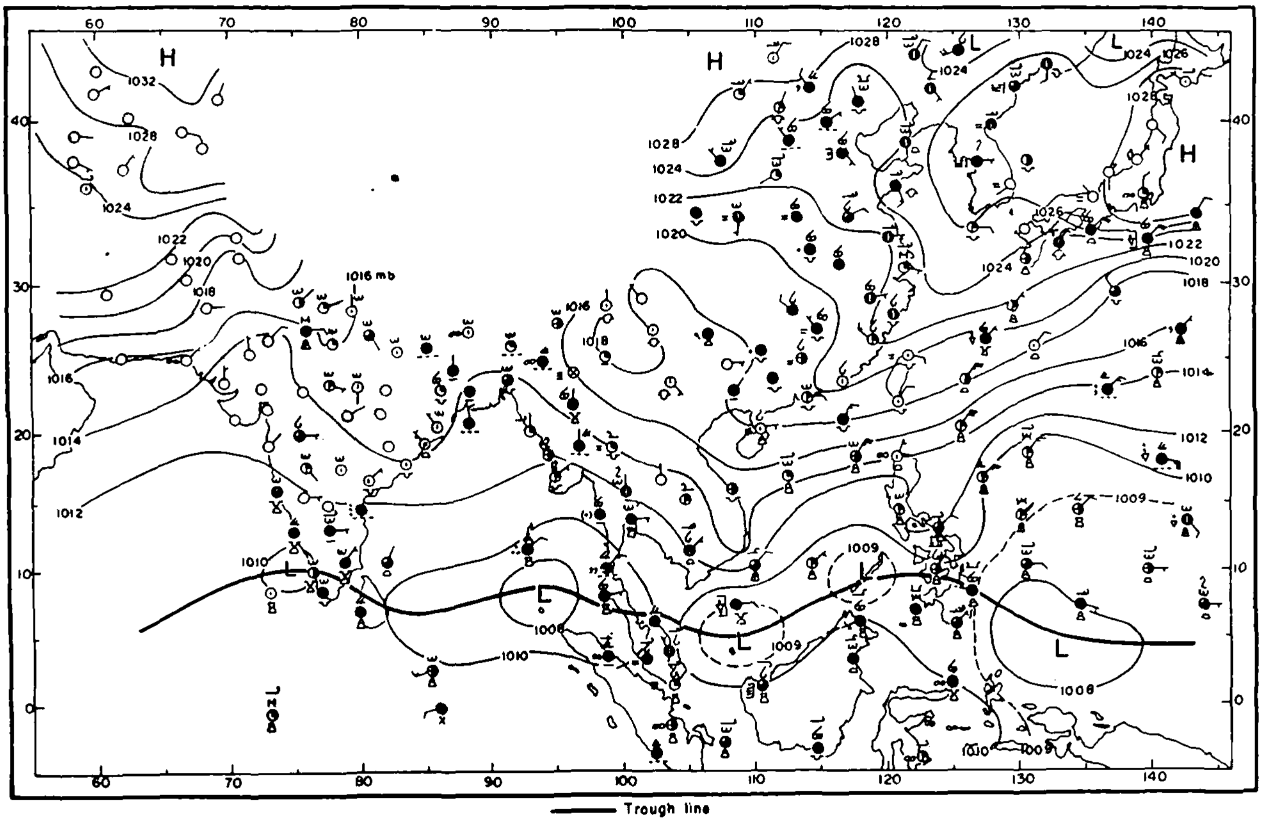



FIG. 16·4 0300 GMT 3 NOV. 71

ESSA - 8 ORBIT 13213 3 NOV. 71 0303 GMT.

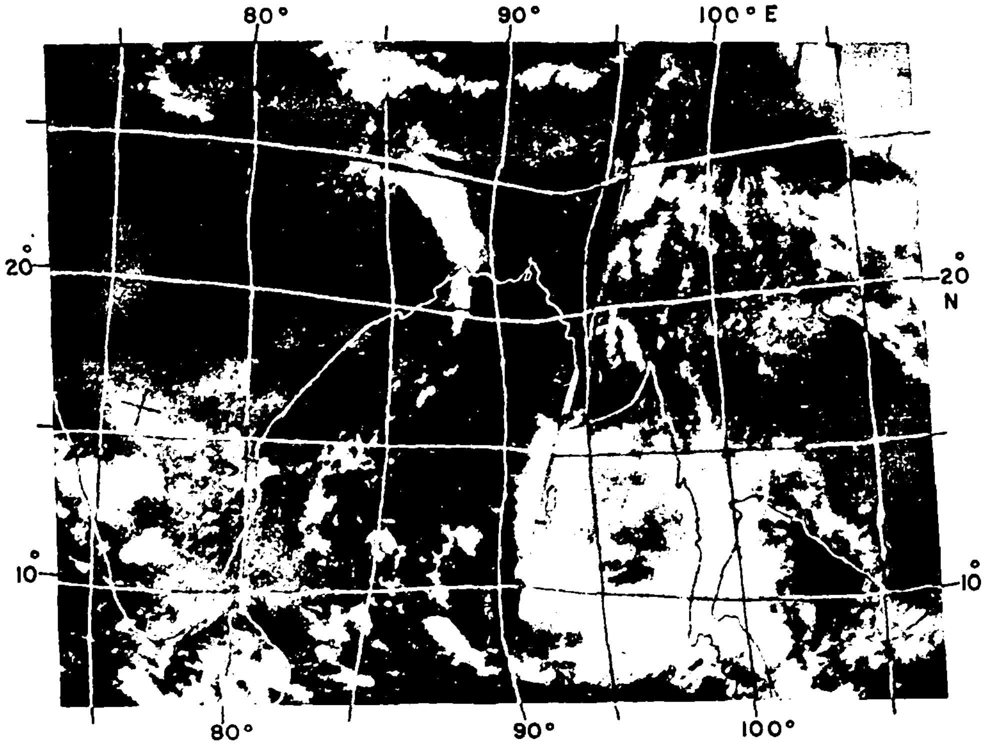
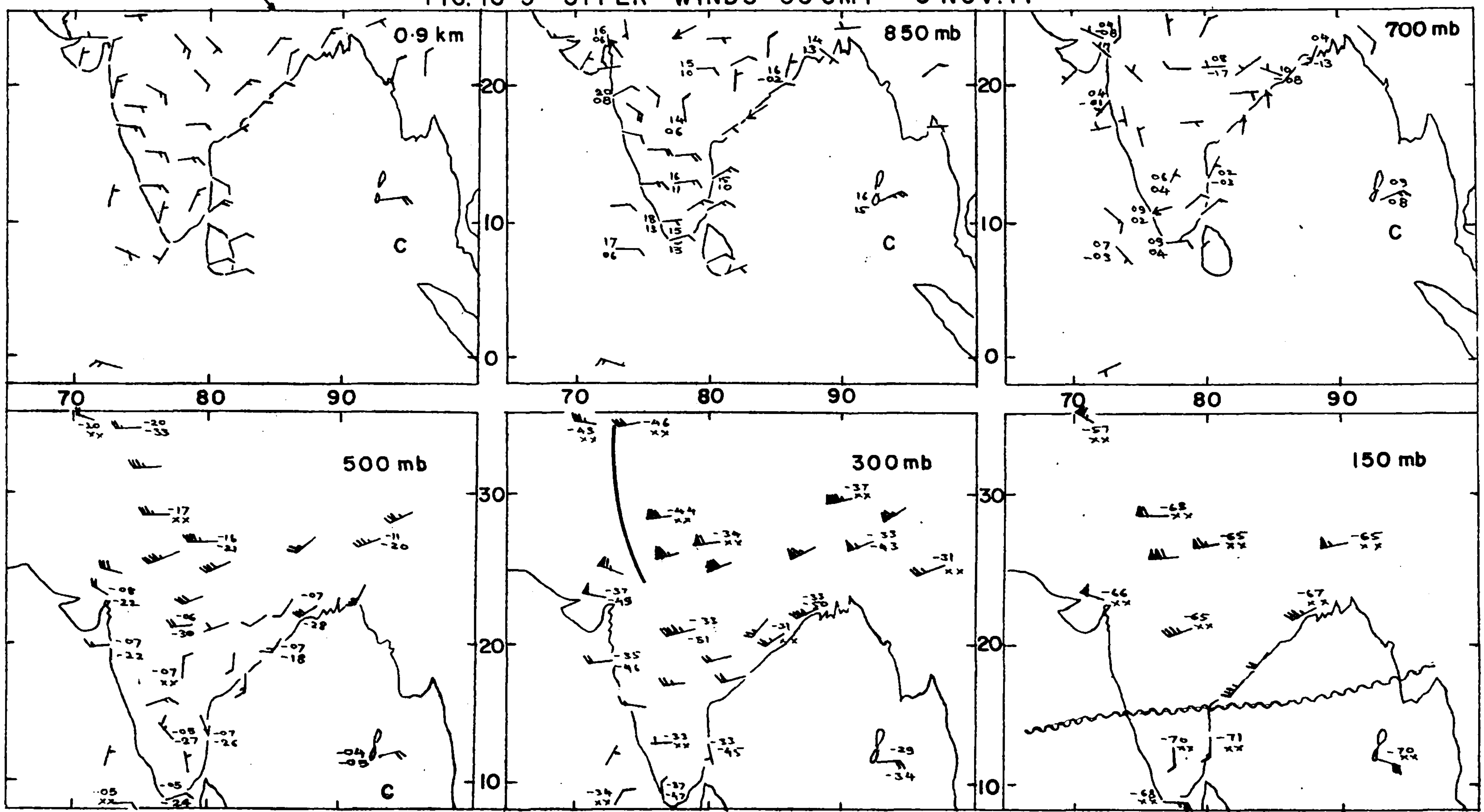


FIG. 16·5 UPPER WINDS 00 GMT 3 NOV.71




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

FIG. 16·6 SYNOPTIC CHARTS 0300 GMT 4 NOV. 71

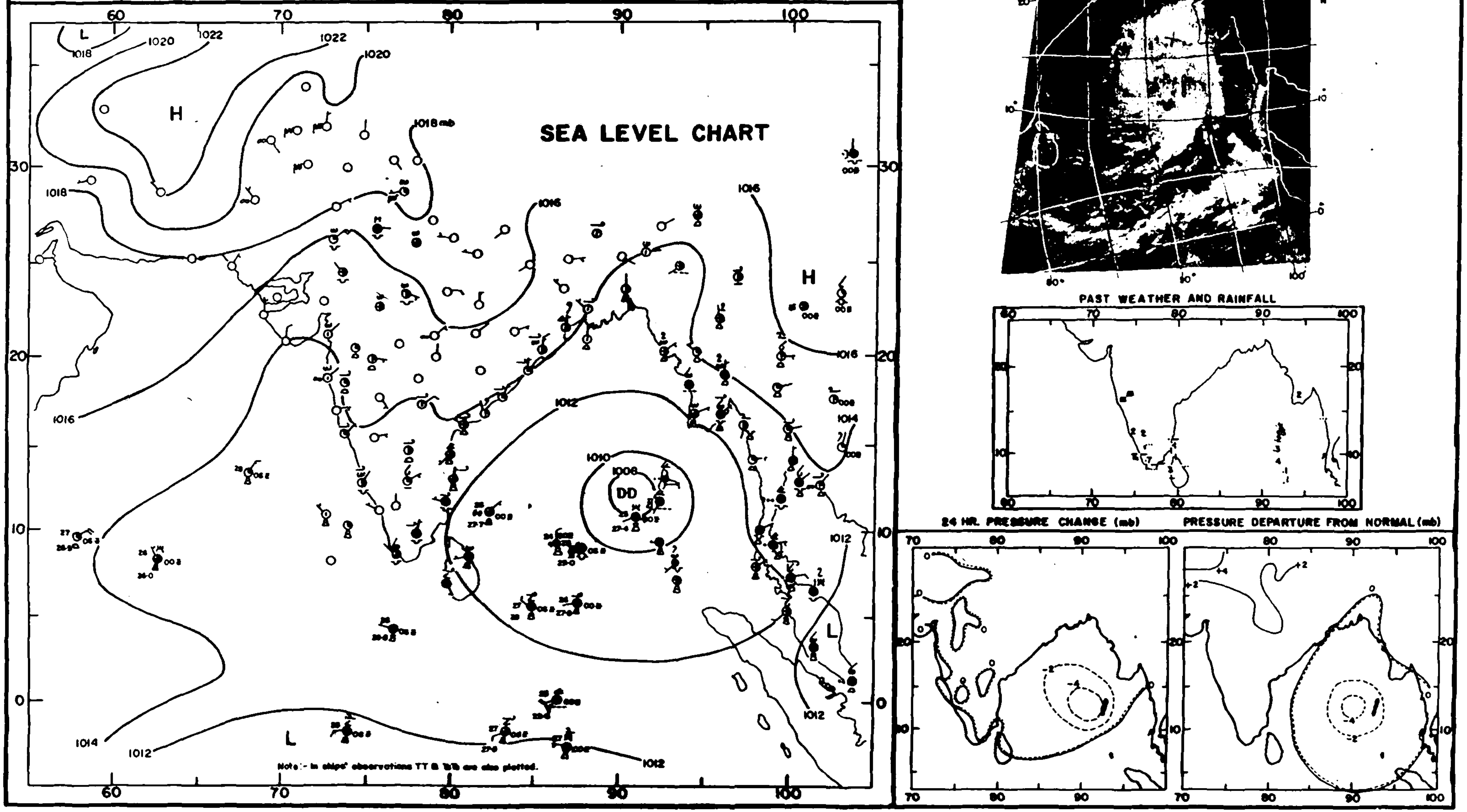
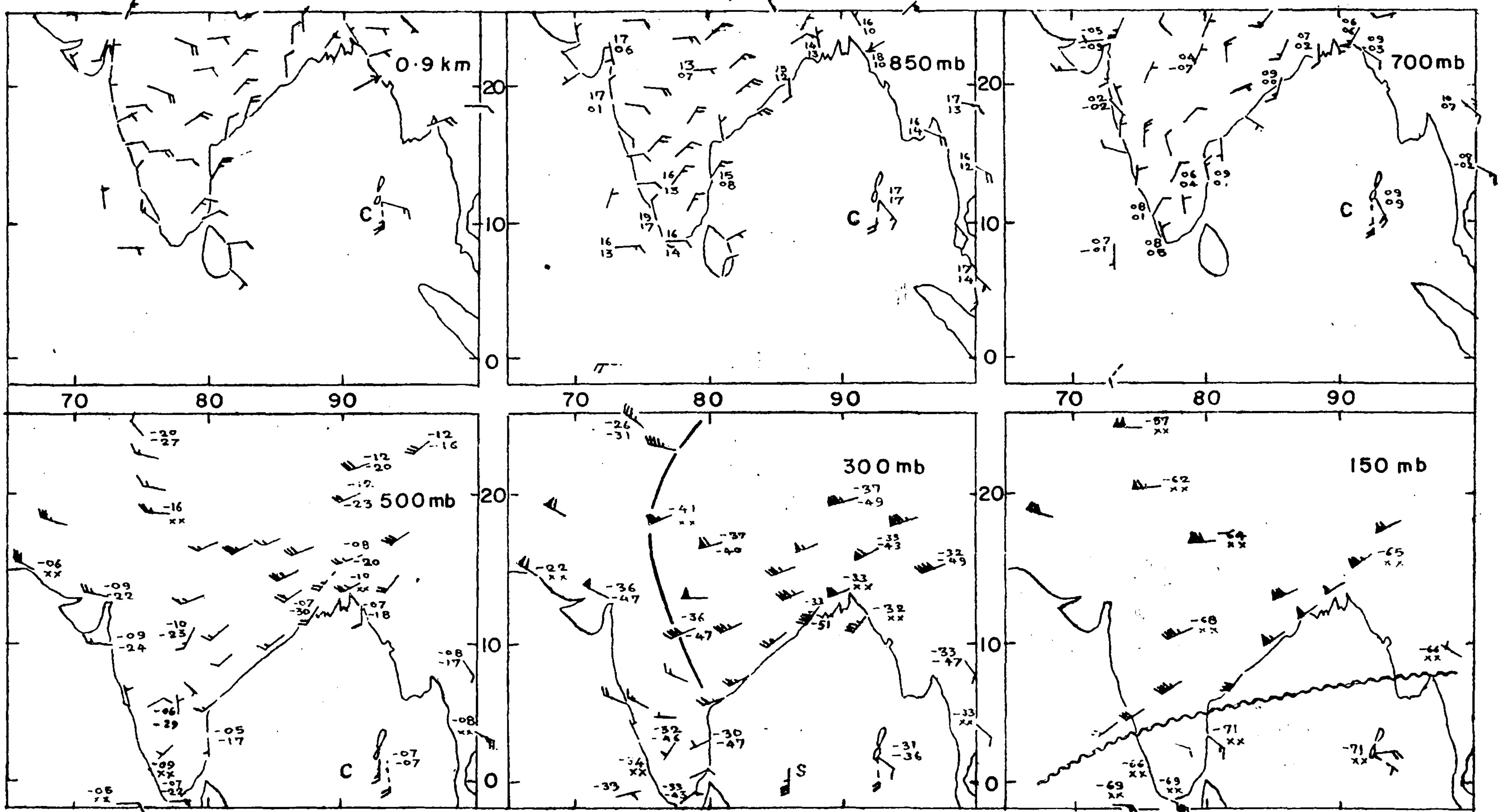


FIG. 16·7 UPPER WINDS 00 GMT 4 NOV. 71




Plotted figures TT & $T_dT_d$ C - Centre of cyclonic circulation —— Trough line ~~~ Ridge line Broken shafts refer to 12Z data.
S - Satellite wind

# FIG. 16·8 SYNOPTIC CHARTS 0300 GMT 5 NOV. 71

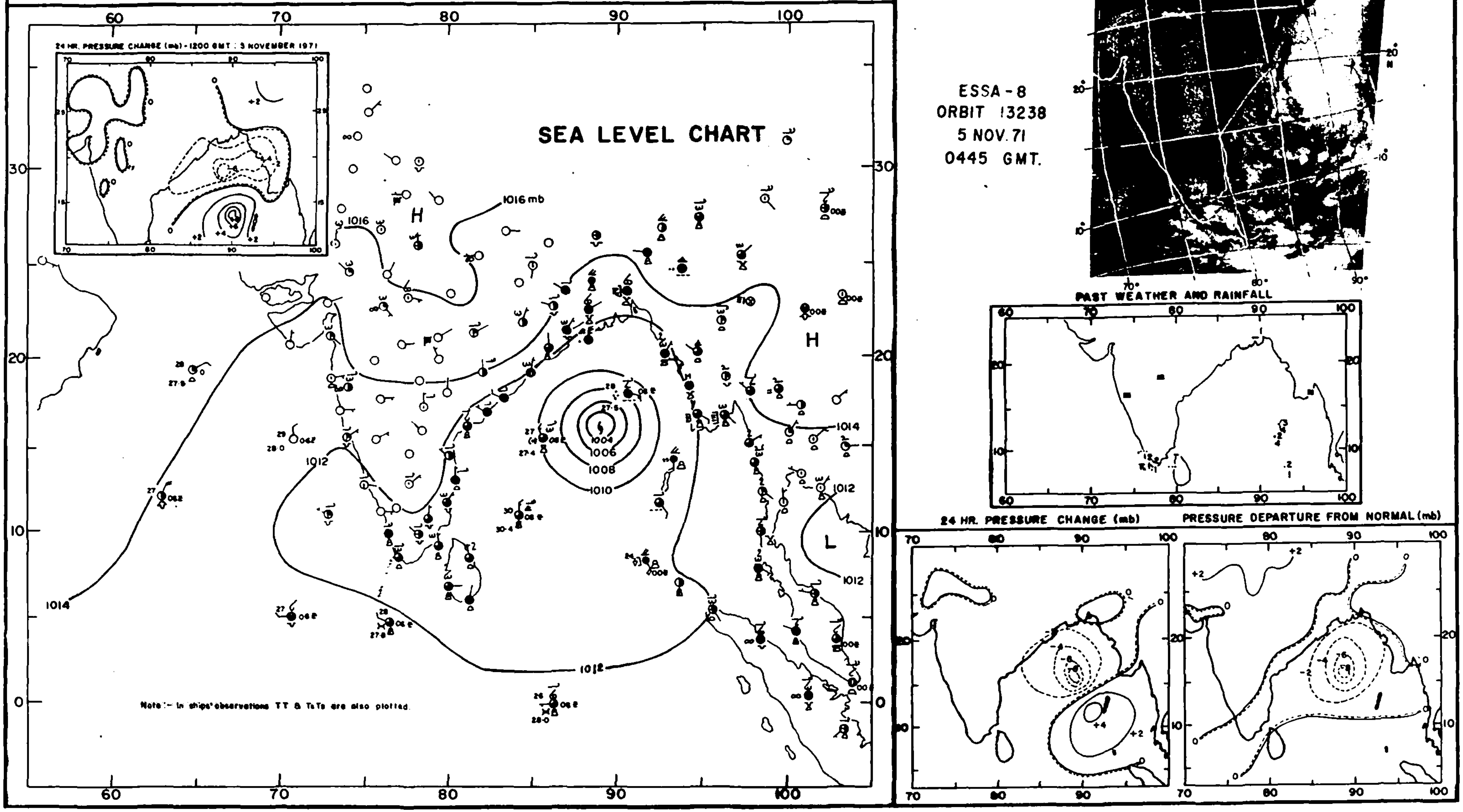
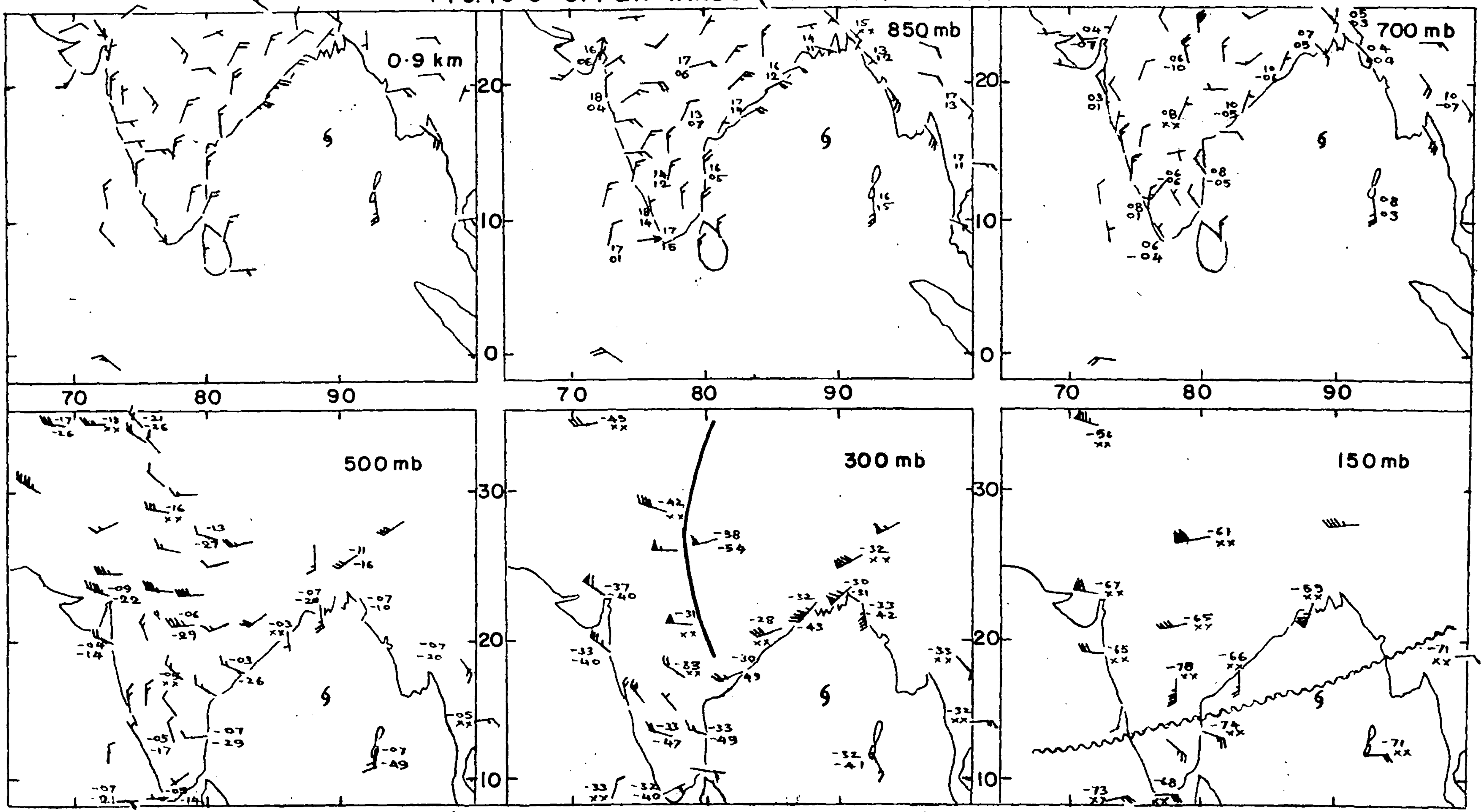


FIG. 16·9 UPPER WINDS , 00 GMT 5 NOV. 71




Trough line    ϛ Cyclonic storm    Plotted figures TT & $T_dT_d$    Ridge line

FIG. 16·10 SYNOPTIC CHARTS 0300 GMT 6 NOV. 71

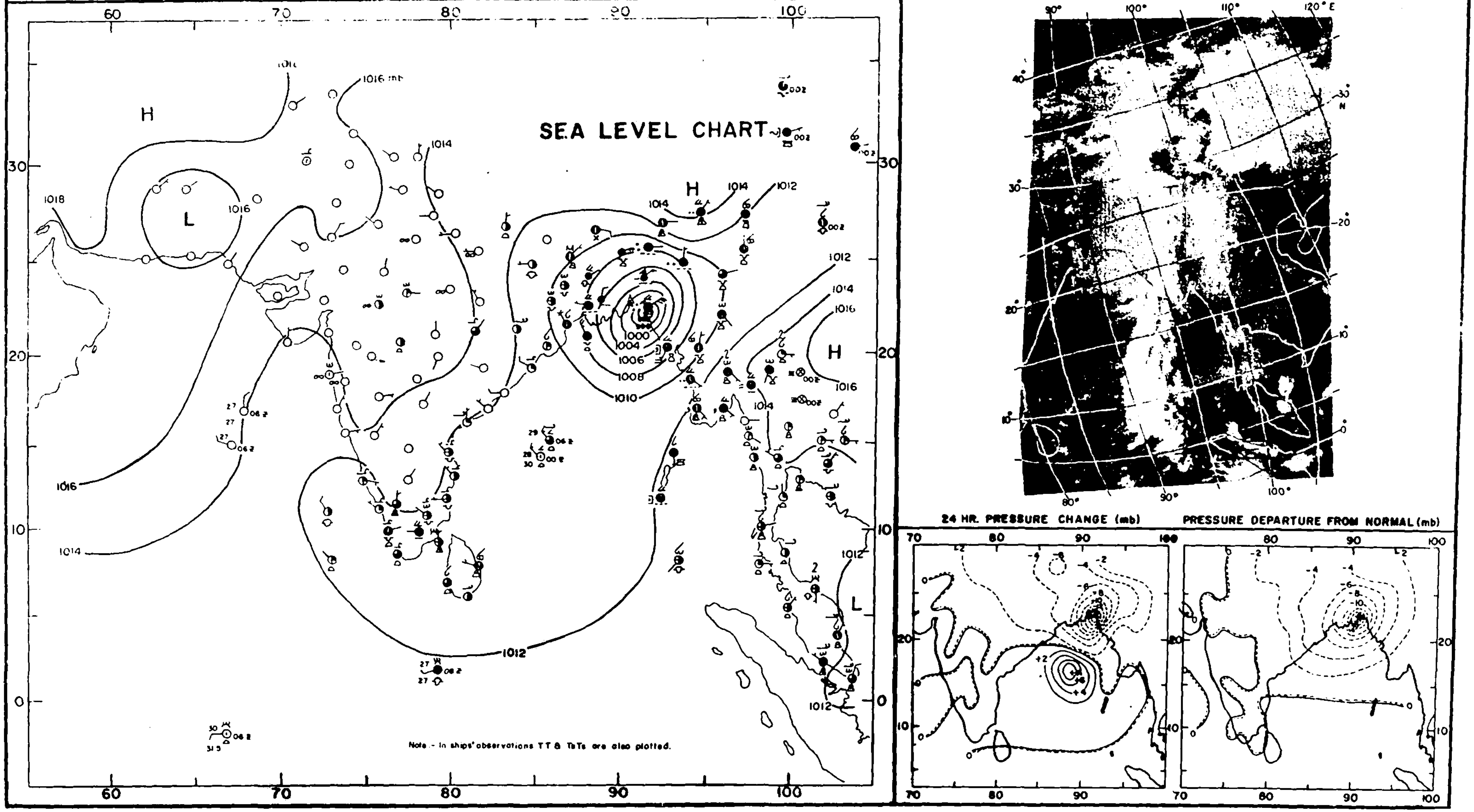
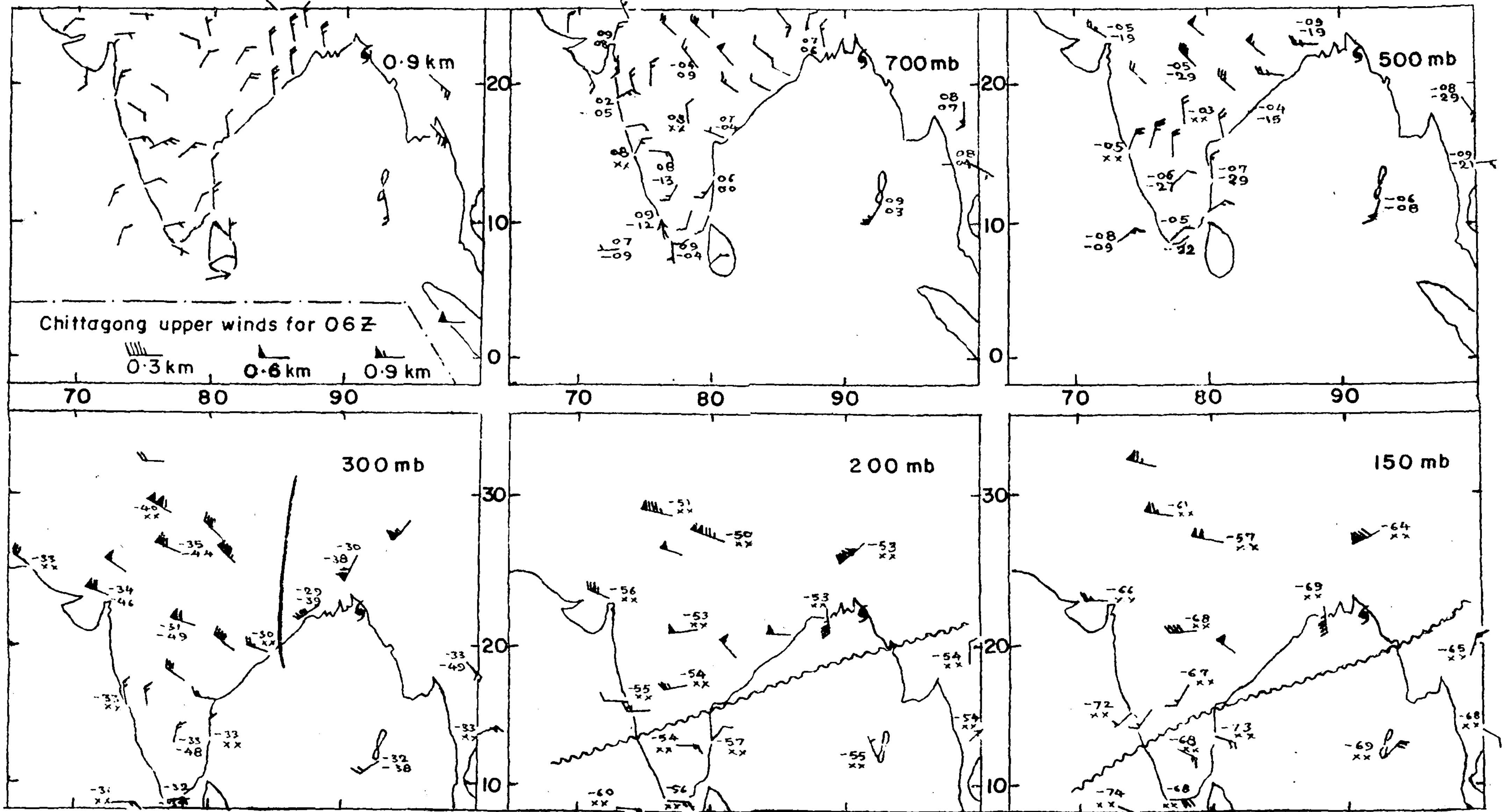


FIG. 16·11 UPPER WINDS 00 GMT 6·NOV. 71




Trough line  Ridge line  Cyclonic storm  Plotted figures TT & $T_dT_d$

FIG. 17·1 SYNOPTIC CHARTS 0300 GMT 5 NOV. 66

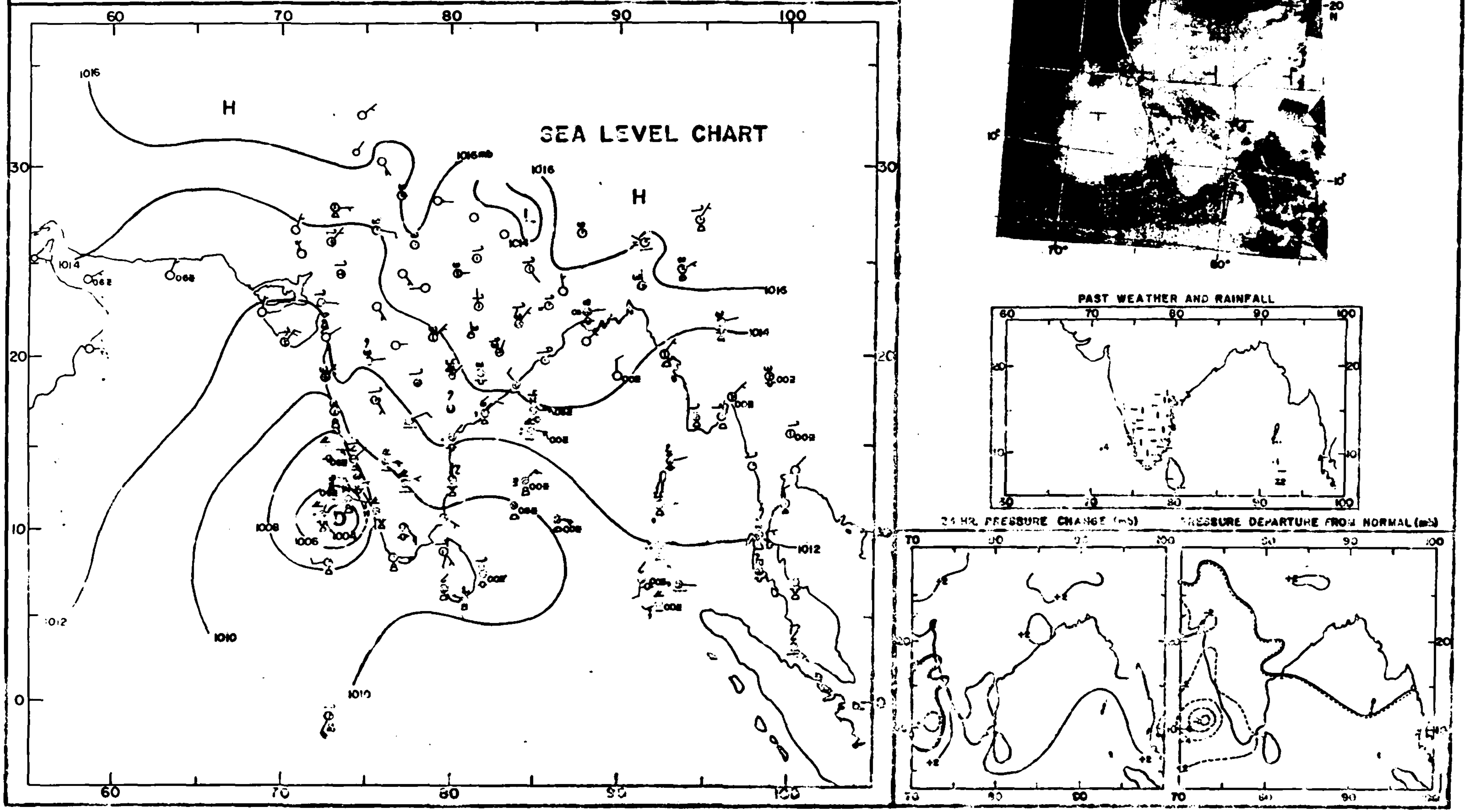
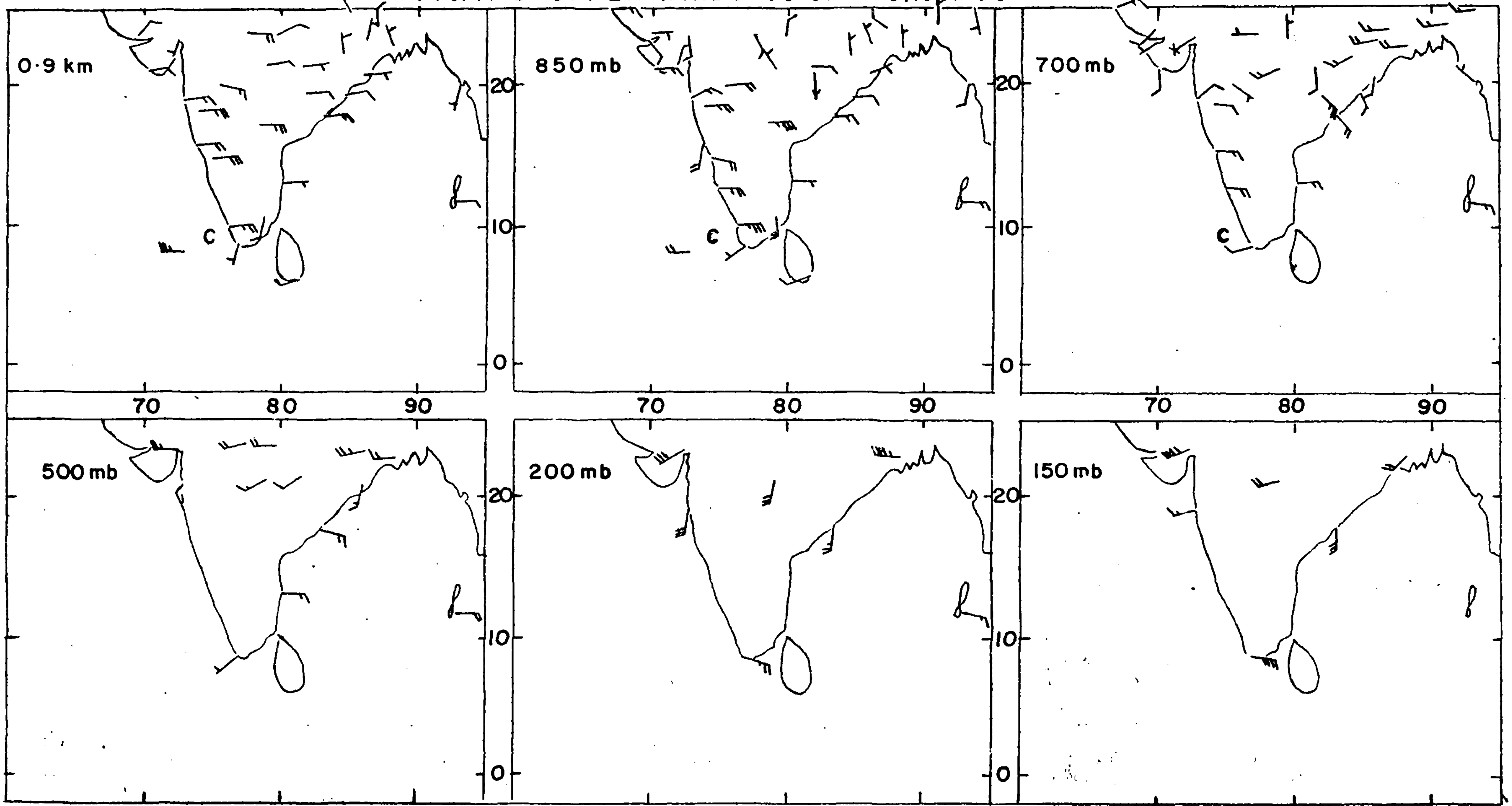


FIG. 17·2 UPPER WINDS 00 GMT 5NOV. 66




C- Centre of cyclonic circulation

FIG 17.3 SYNOPTIC CHARTS 0300 GMT 6 NOV. 66

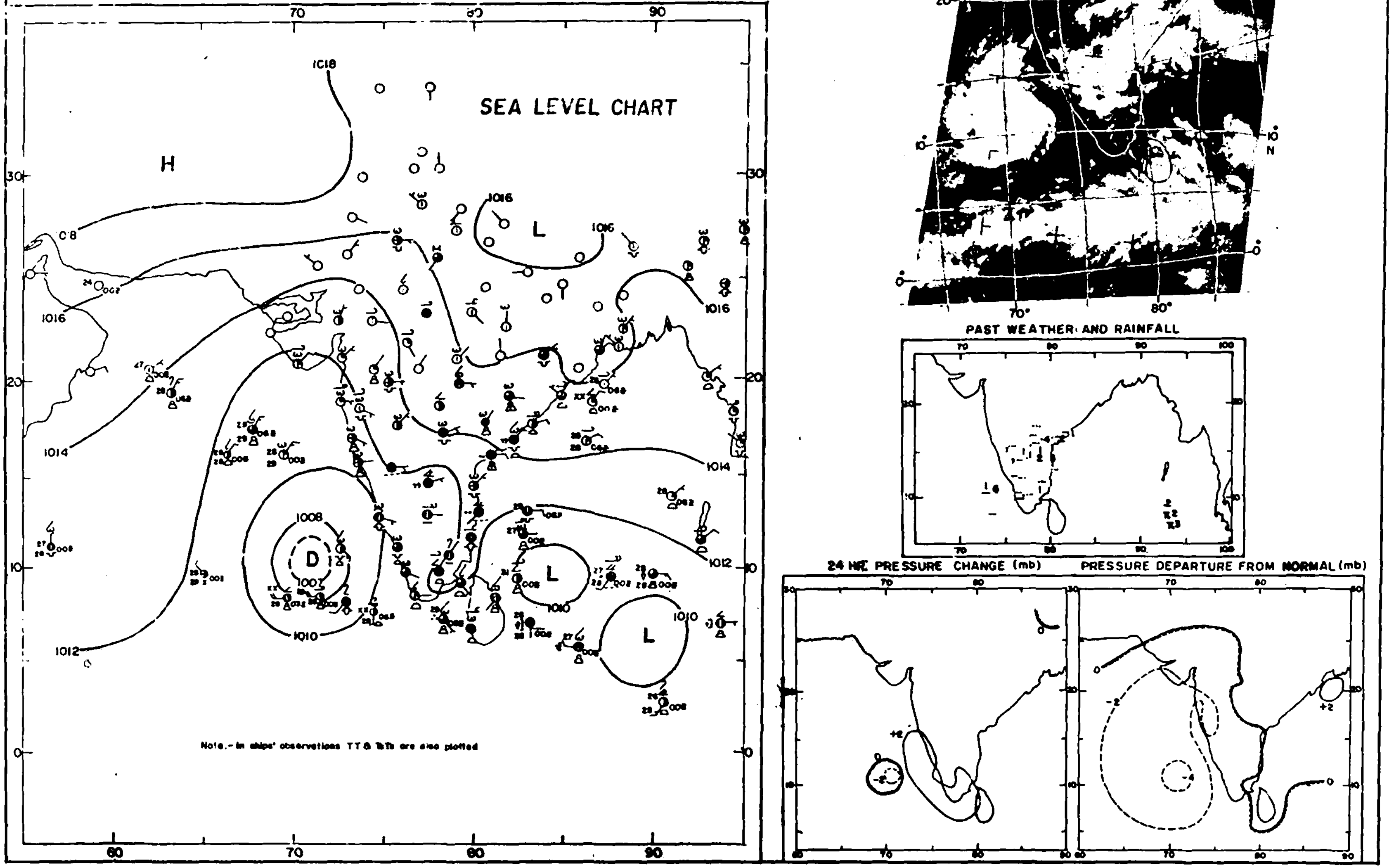
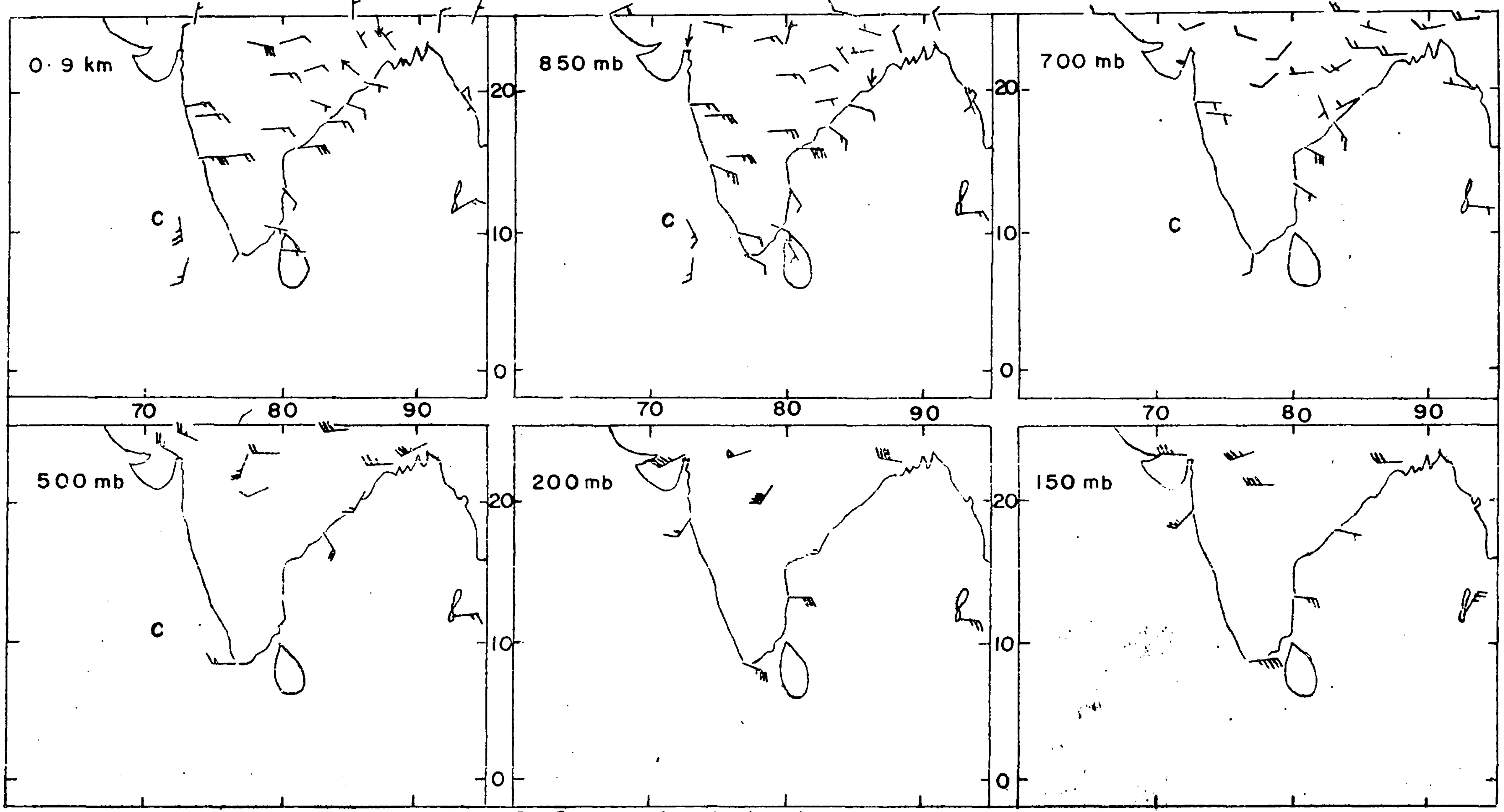


FIG. 17·4 UPPER WINDS 00 GMT 6 NOV. 66




C - Centre of cyclonic circulation

FIG. 17·5 SYNOPTIC CHARTS 0300 GMT 7 NOV. 66

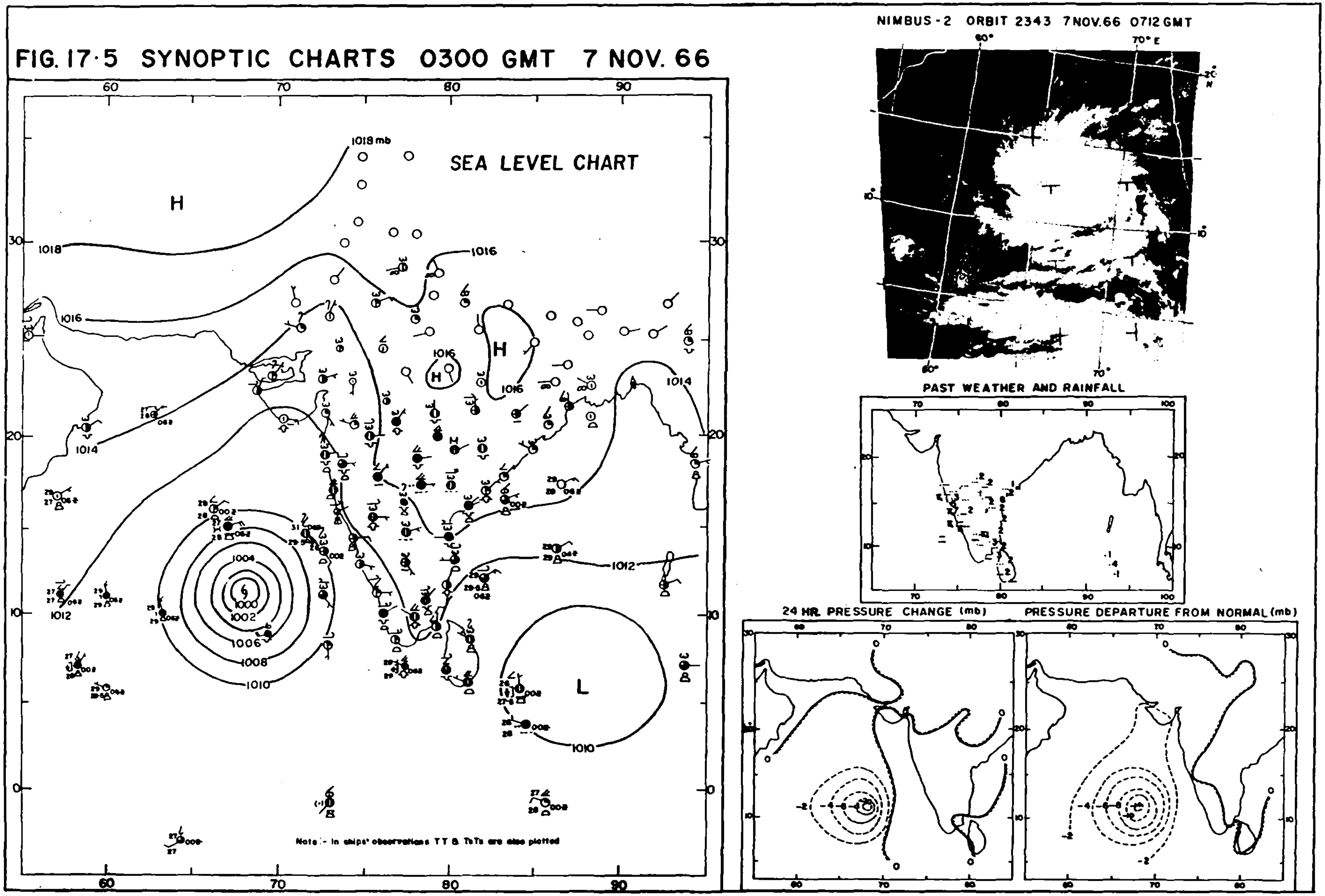


FIG. 17·6 SYNOPTIC CHARTS 0300 GMT 8 NOV. 66

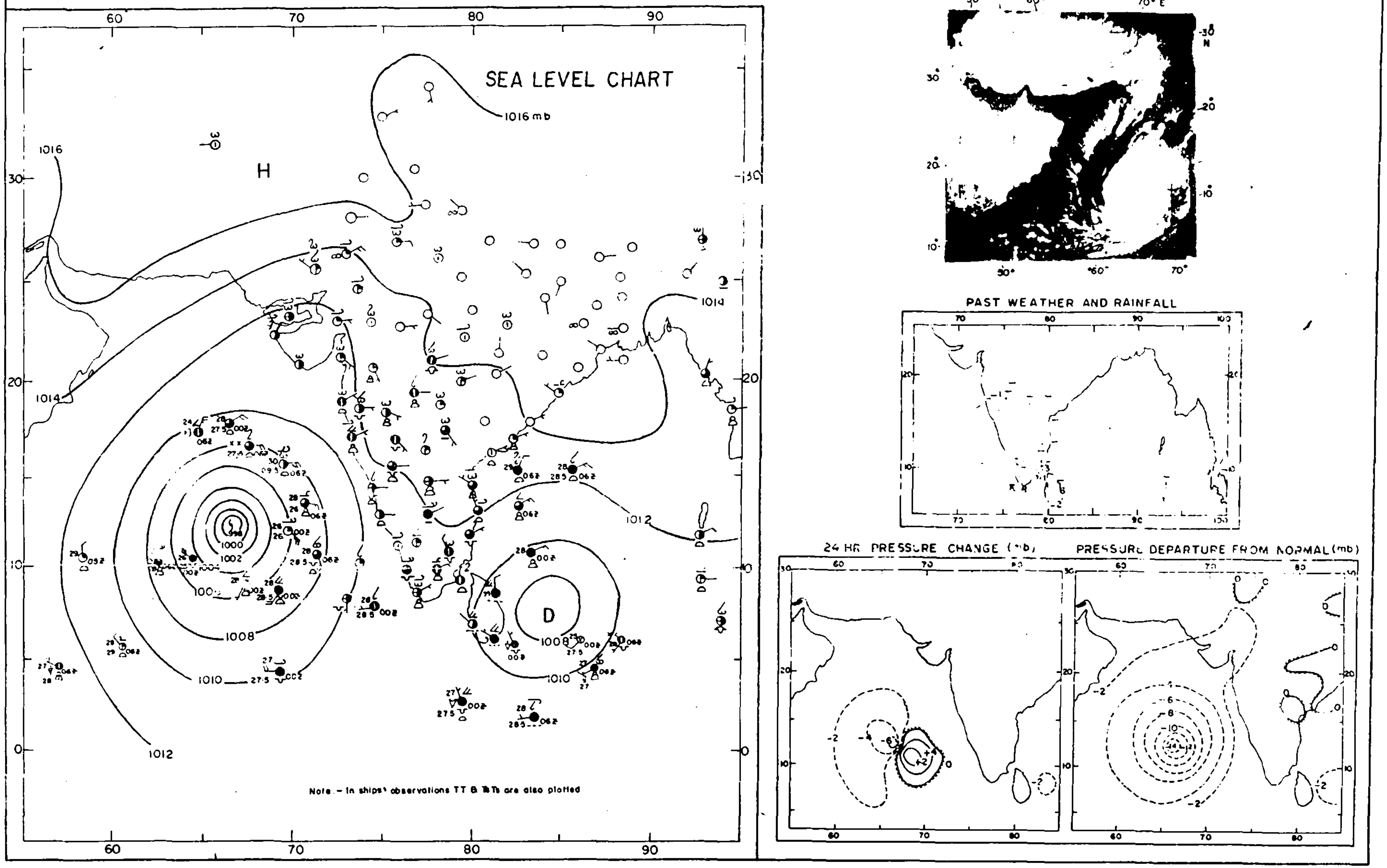
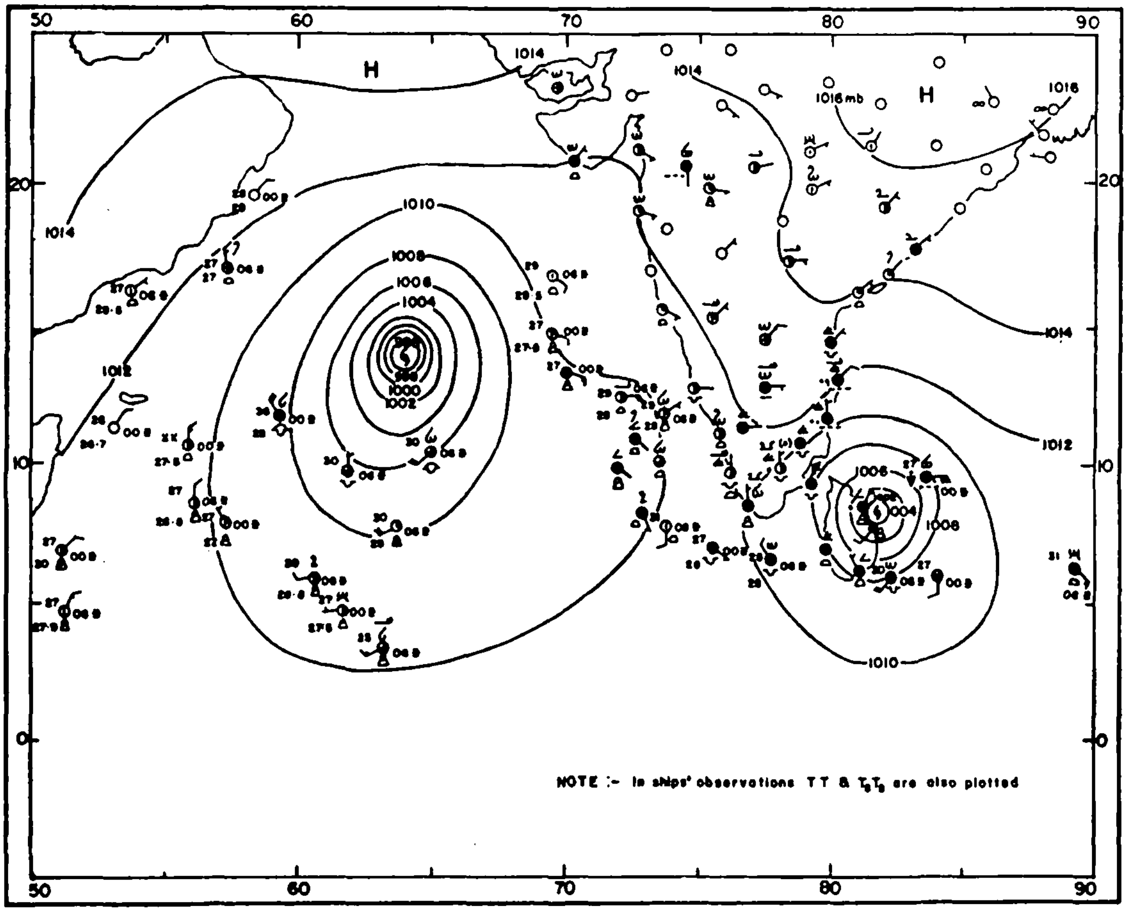


FIG. 17·7 SEA LEVEL CHART 0300 GMT 9 NOV. 66




ESSA-2 ORBIT 3217, 3216 9 NOV. 66 0456 GMT. (0309 GMT)

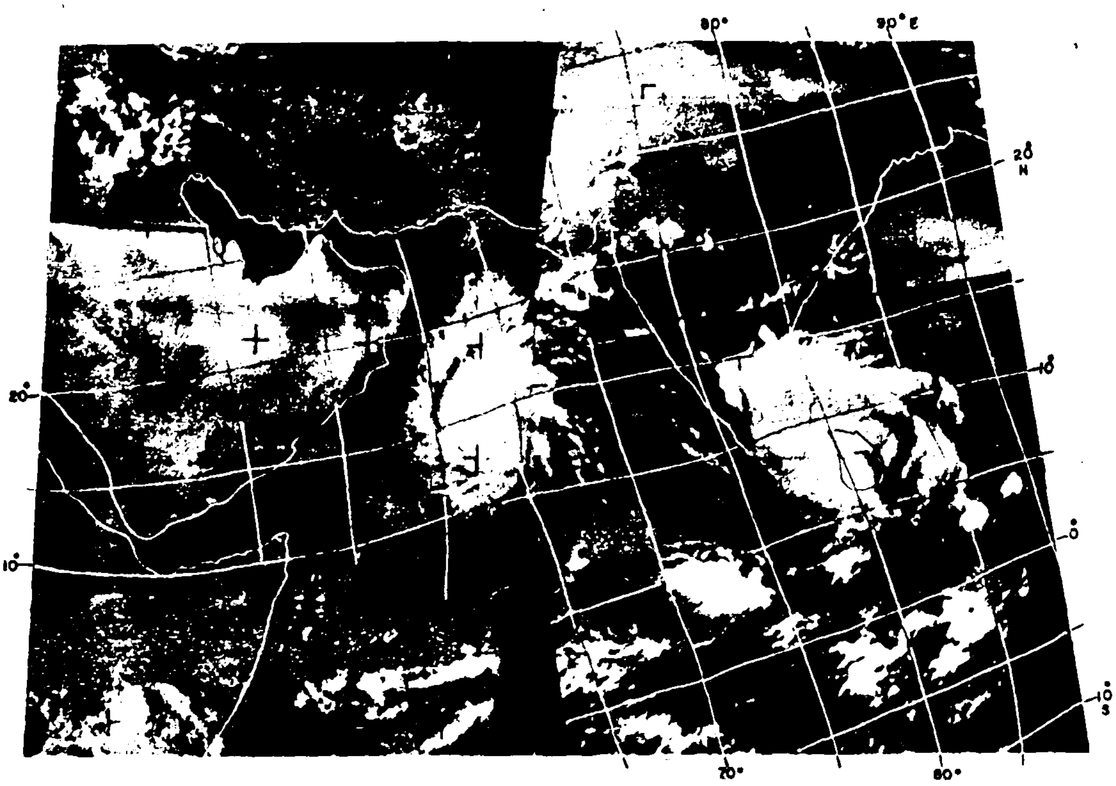
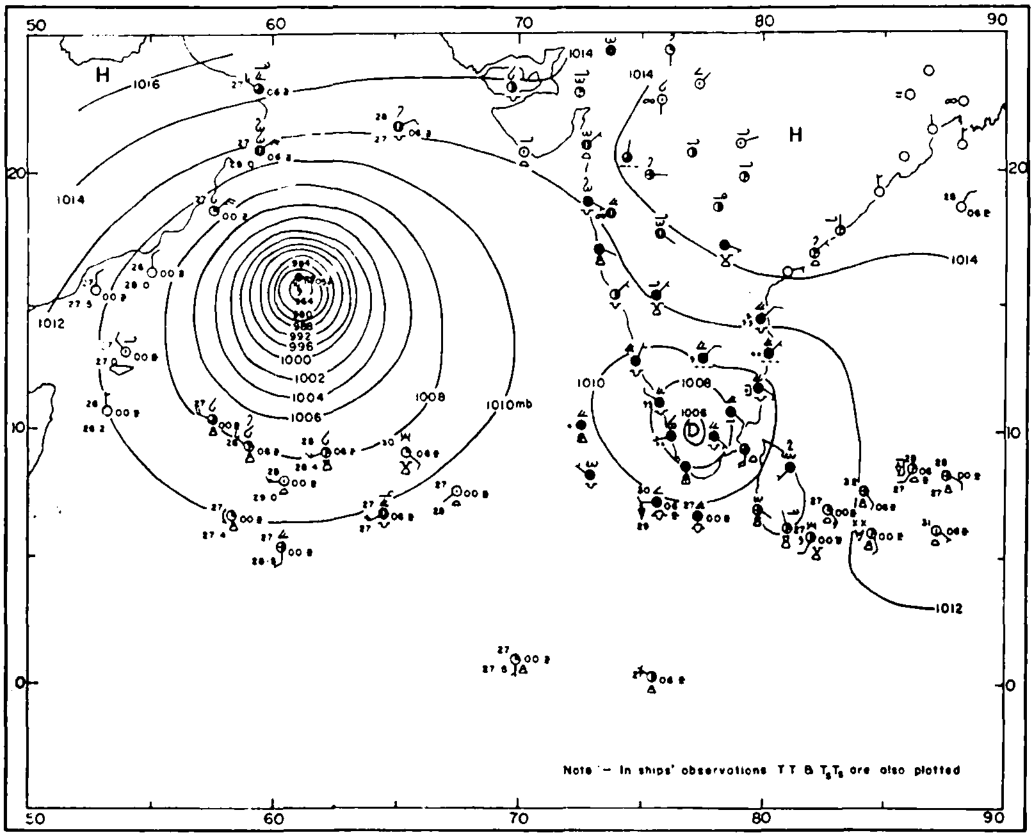
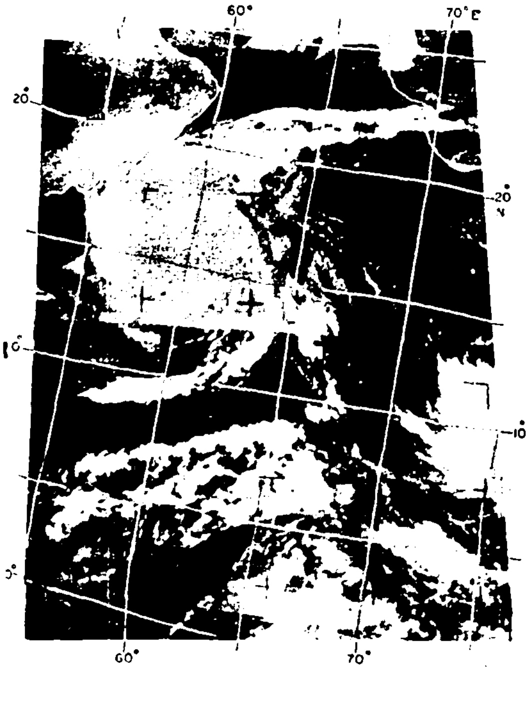


FIG. 17·8 SEA LEVEL CHART 0300 GMT 10 NOV. 66




NIMBUS-2 ORBIT 2383 10NOV. 66 0718GMT




ESSA-2 ORBIT 3242 11 NOV. 66 0414 GMT

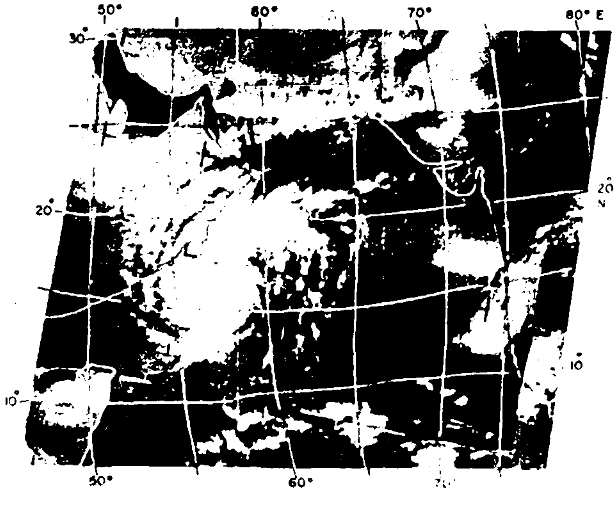


FIG. 18·1 SYNOPTIC CHARTS 0300 GMT 16 DEC. 64

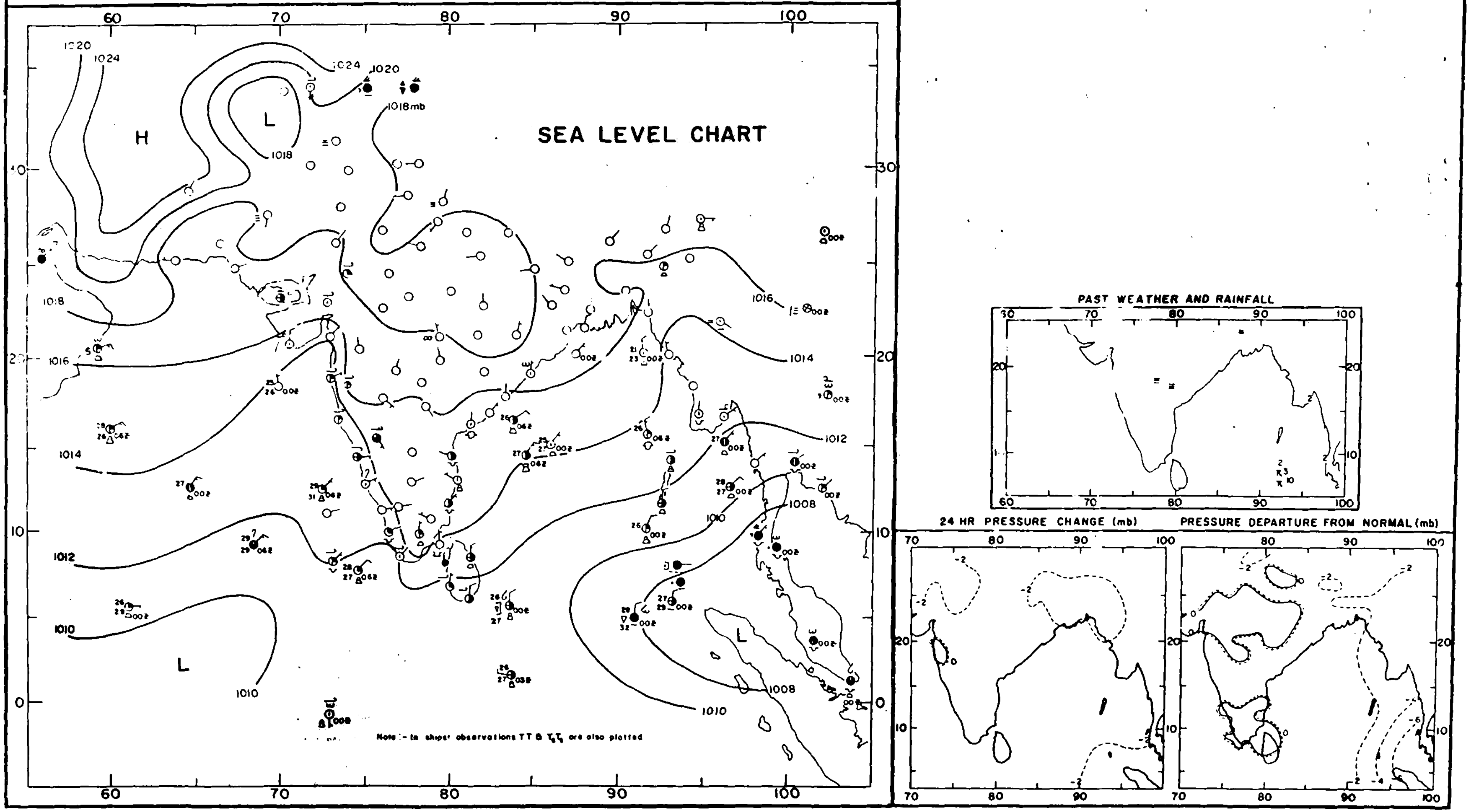


FIG. 18·2 SYNOPTIC CHARTS 0300 GMT 17 DEC. 64

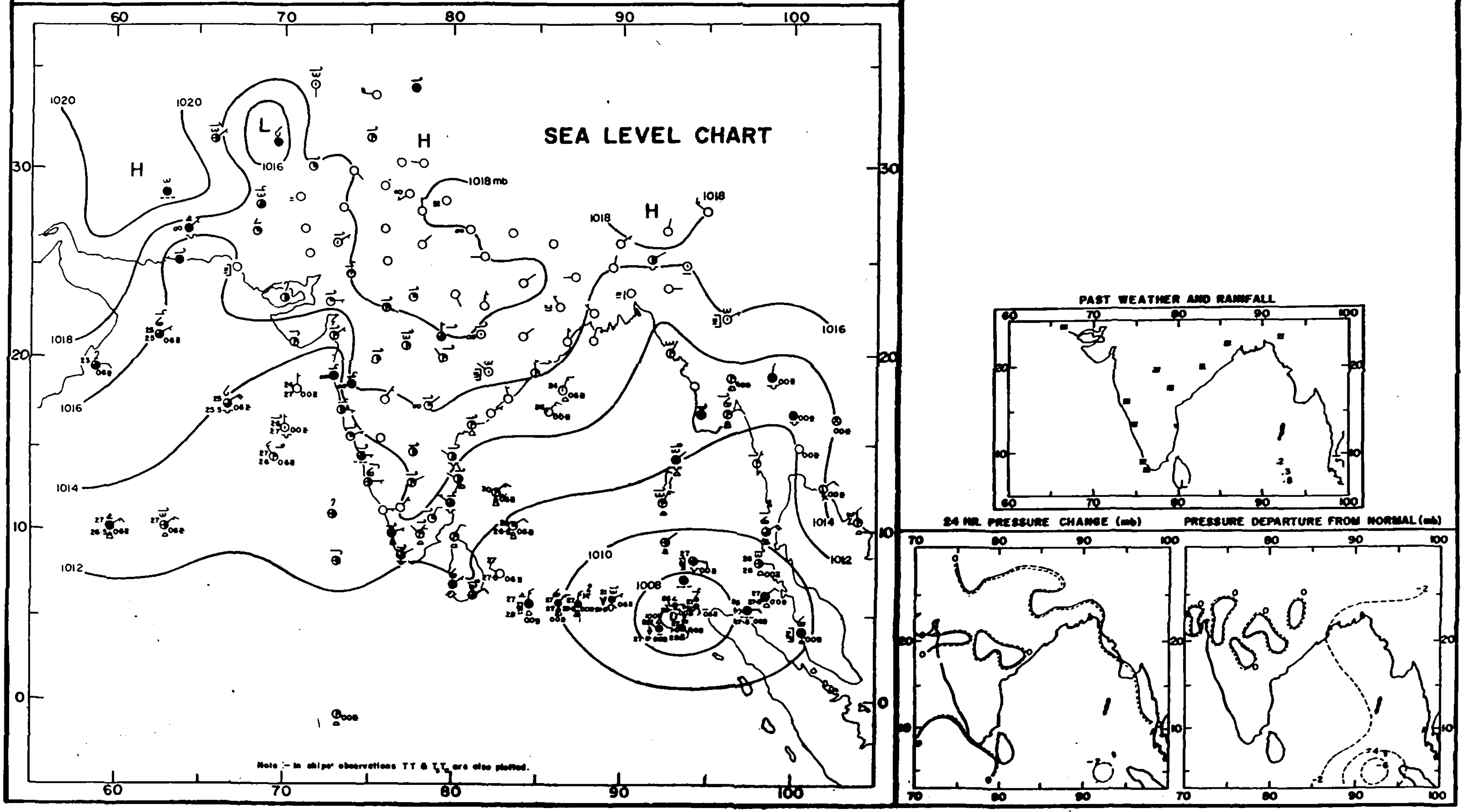


FIG. 18·3 SYNOPTIC CHARTS 0300 GMT 19 DEC. 64

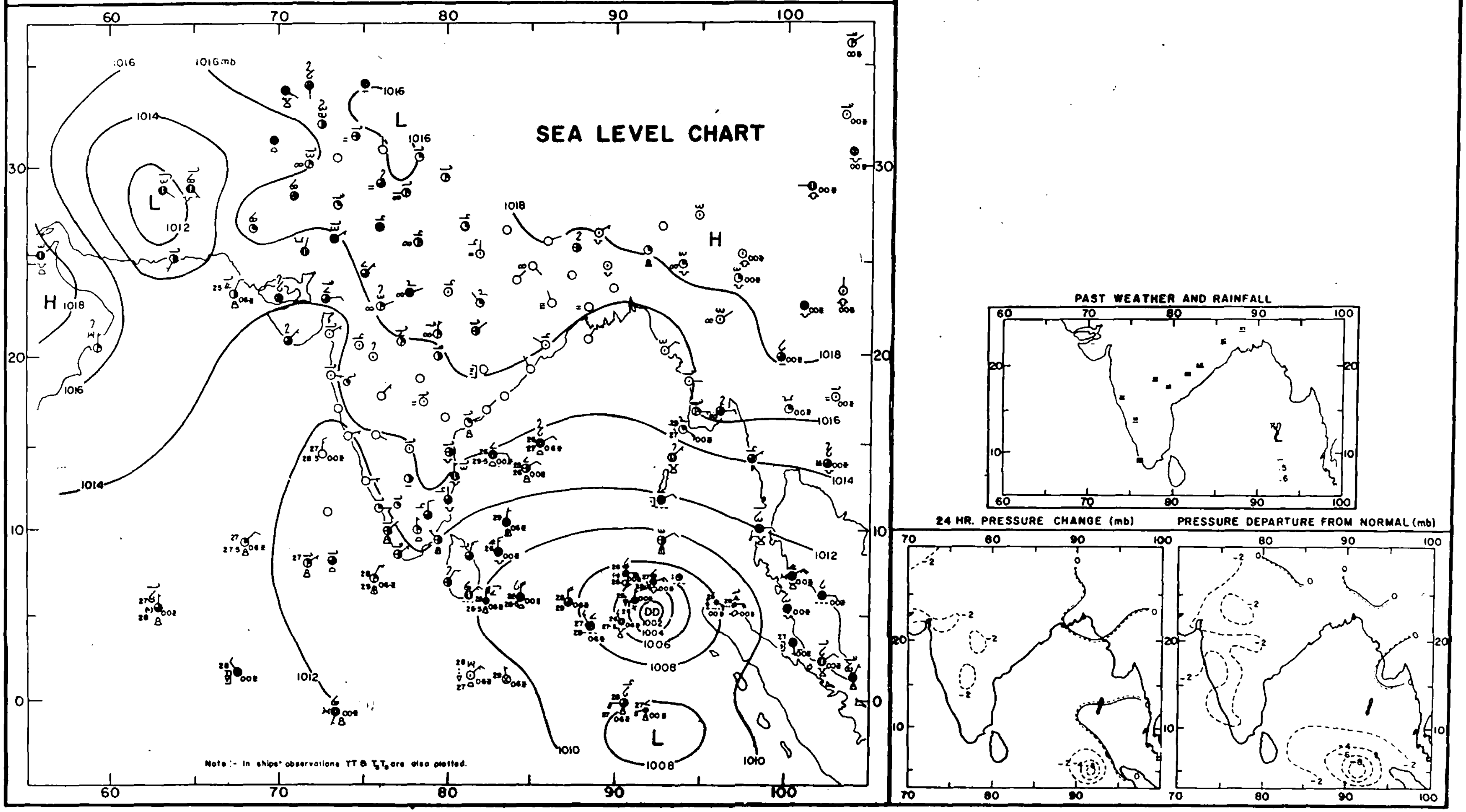
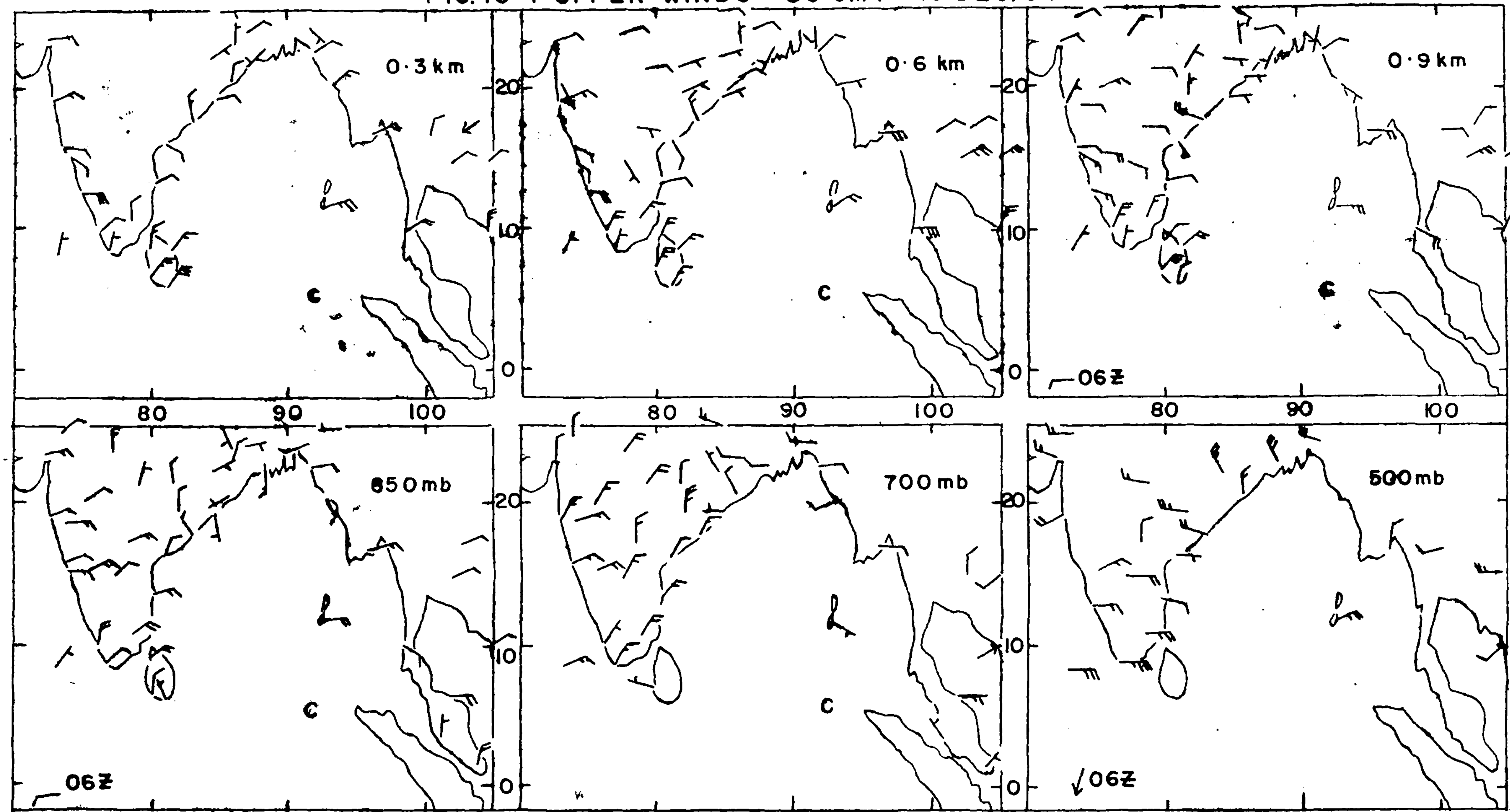
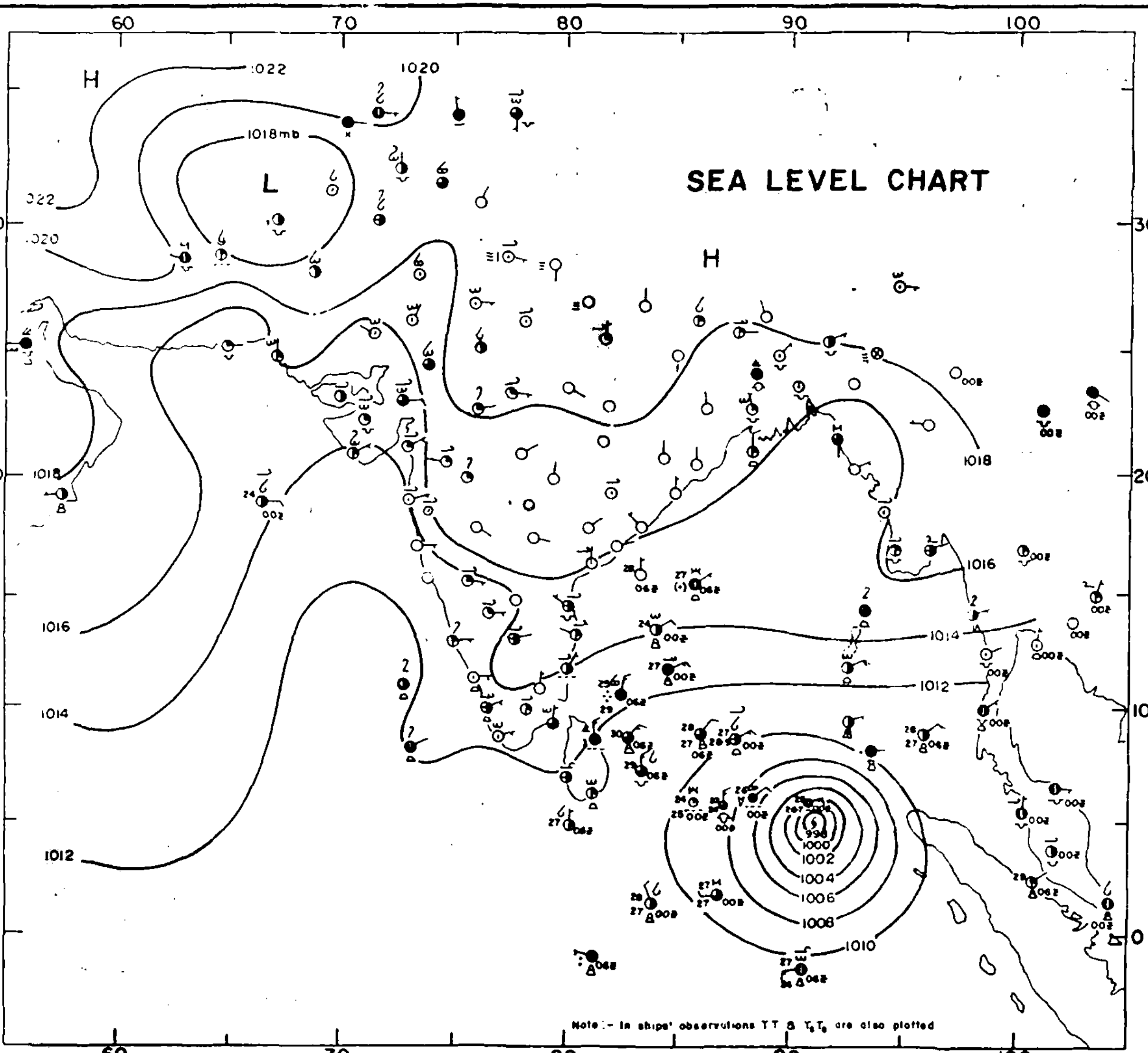


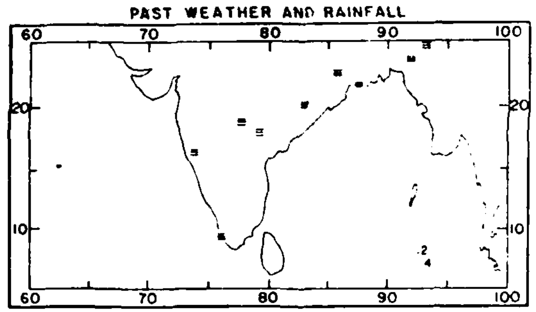
FIG. 18·4 UPPER WINDS 00 GMT 19 DEC. 64

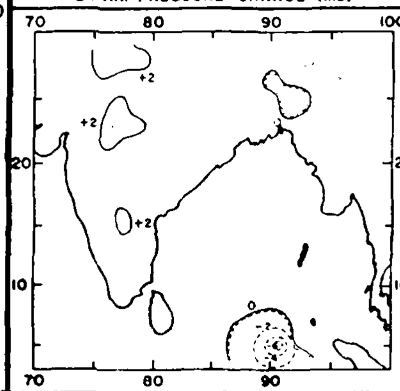



C - Centre of cyclonic circulation

# FIG. 18·5 SYNOPTIC CHARTS 0300 GMT 20 DEC. 64



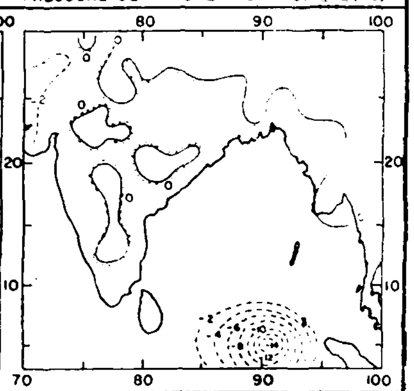
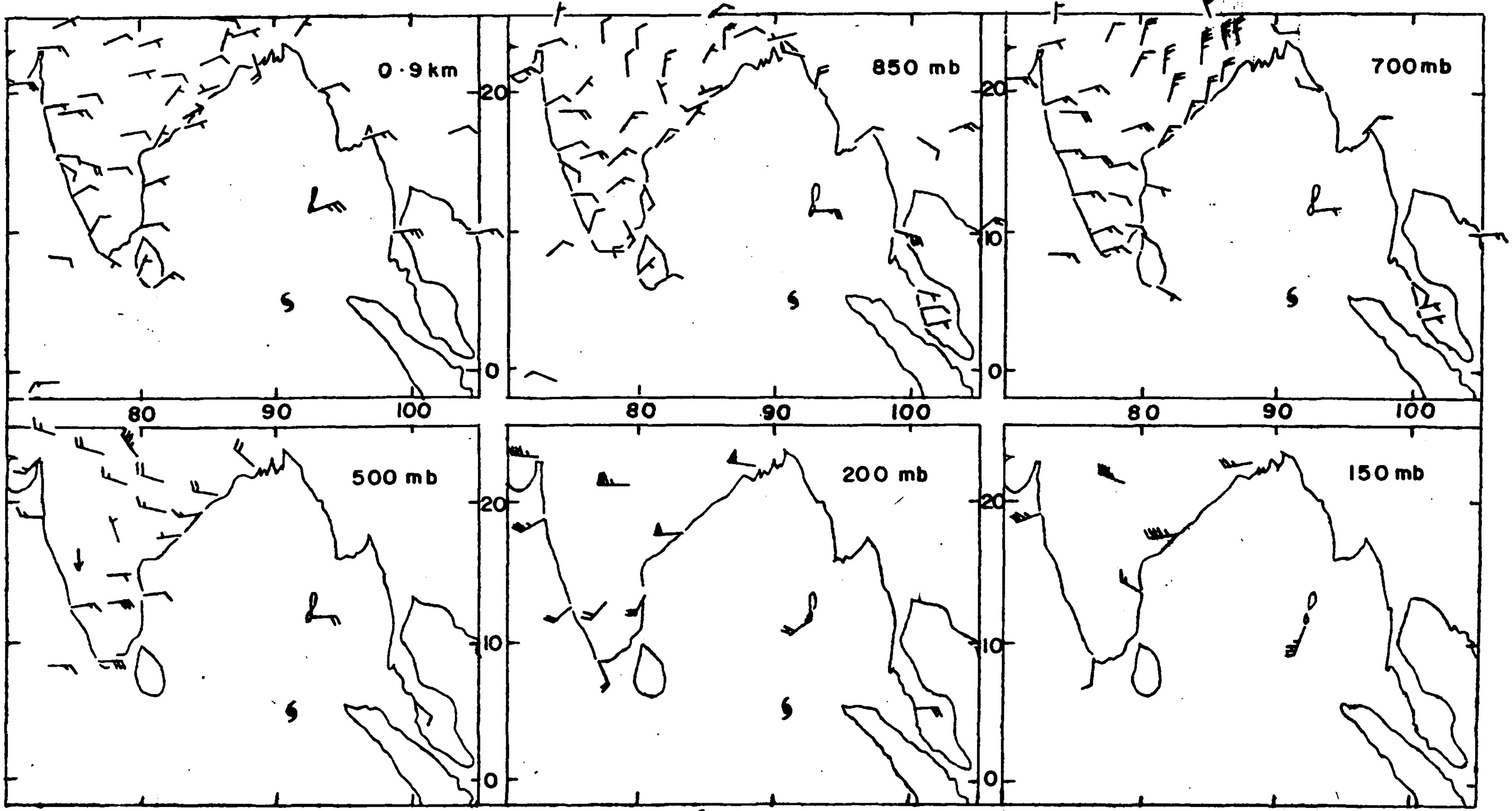
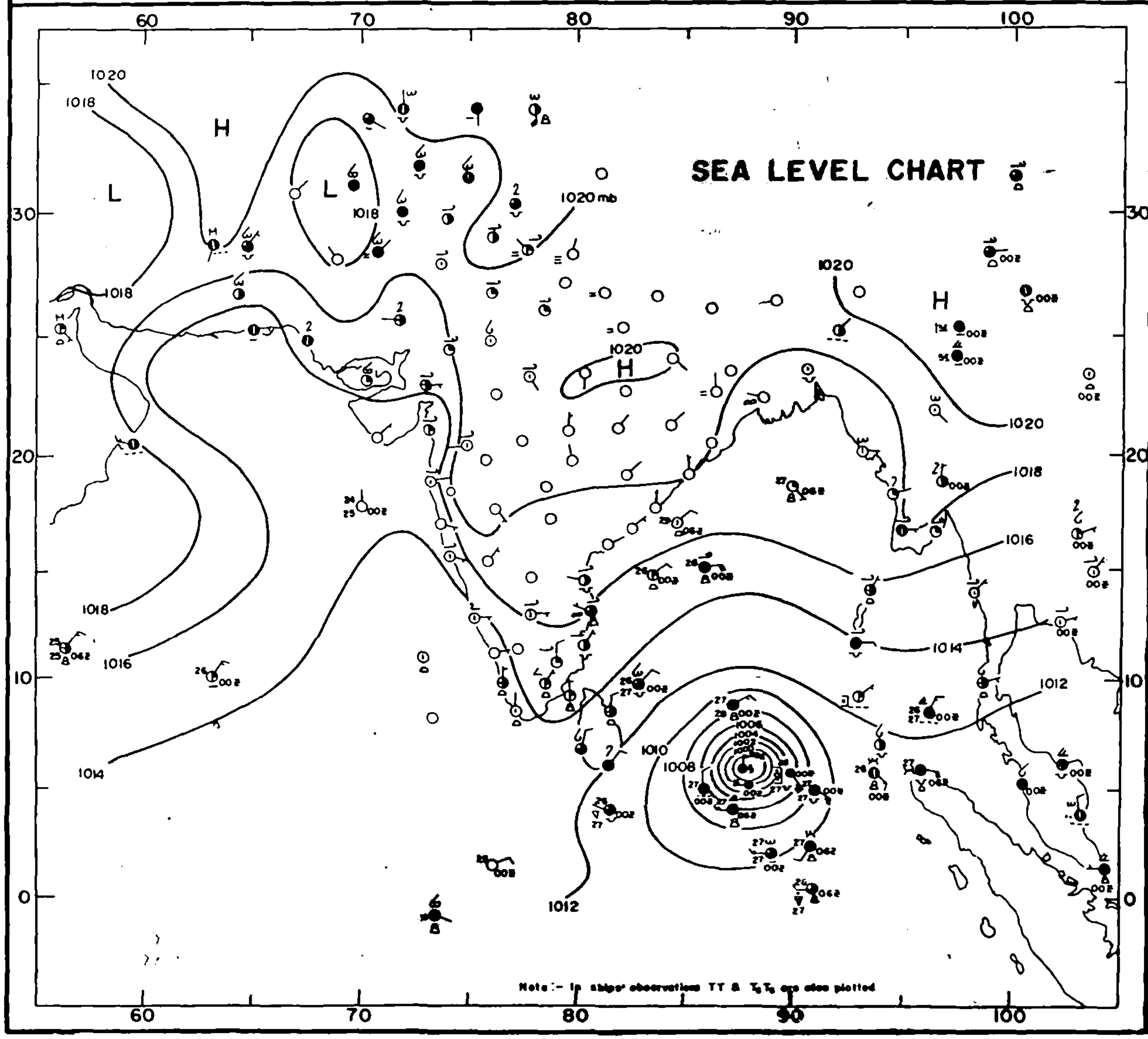



FIG. 18·6 UPPER WINDS 00 GMT 20 DEC. 64



# FIG. 18·7 SYNOPTIC CHARTS 0300 GMT 21 DEC. 64



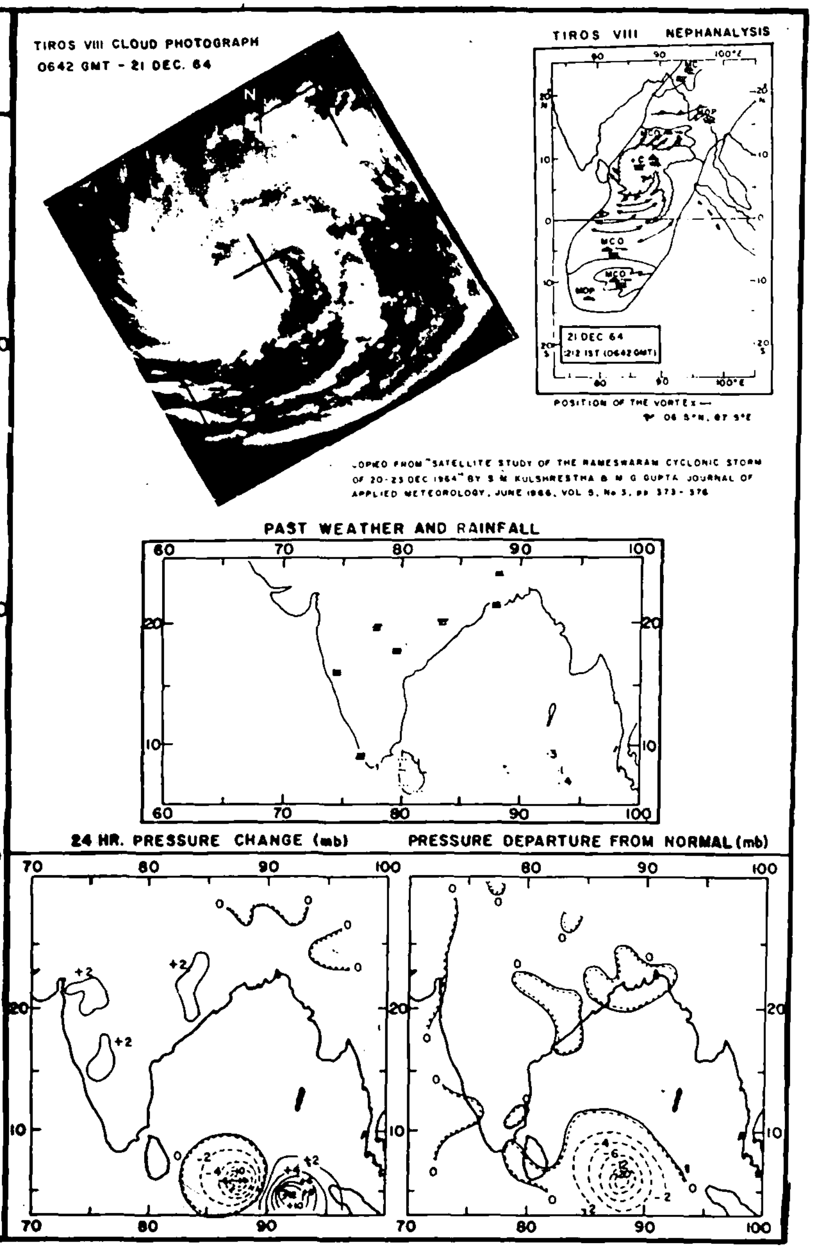



FIG. 18·8 UPPER WINDS 00 GMT 21 DEC. 64

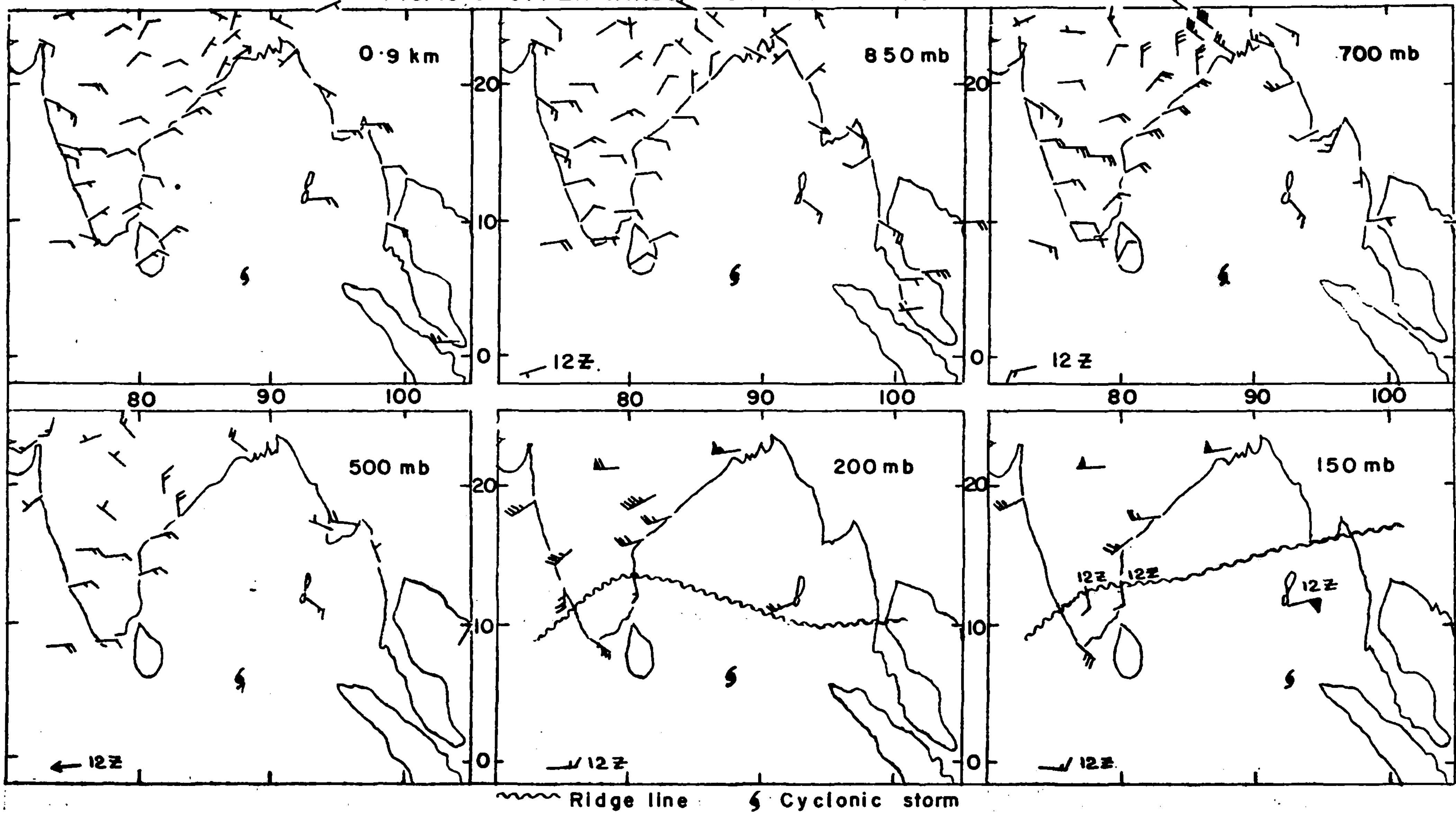
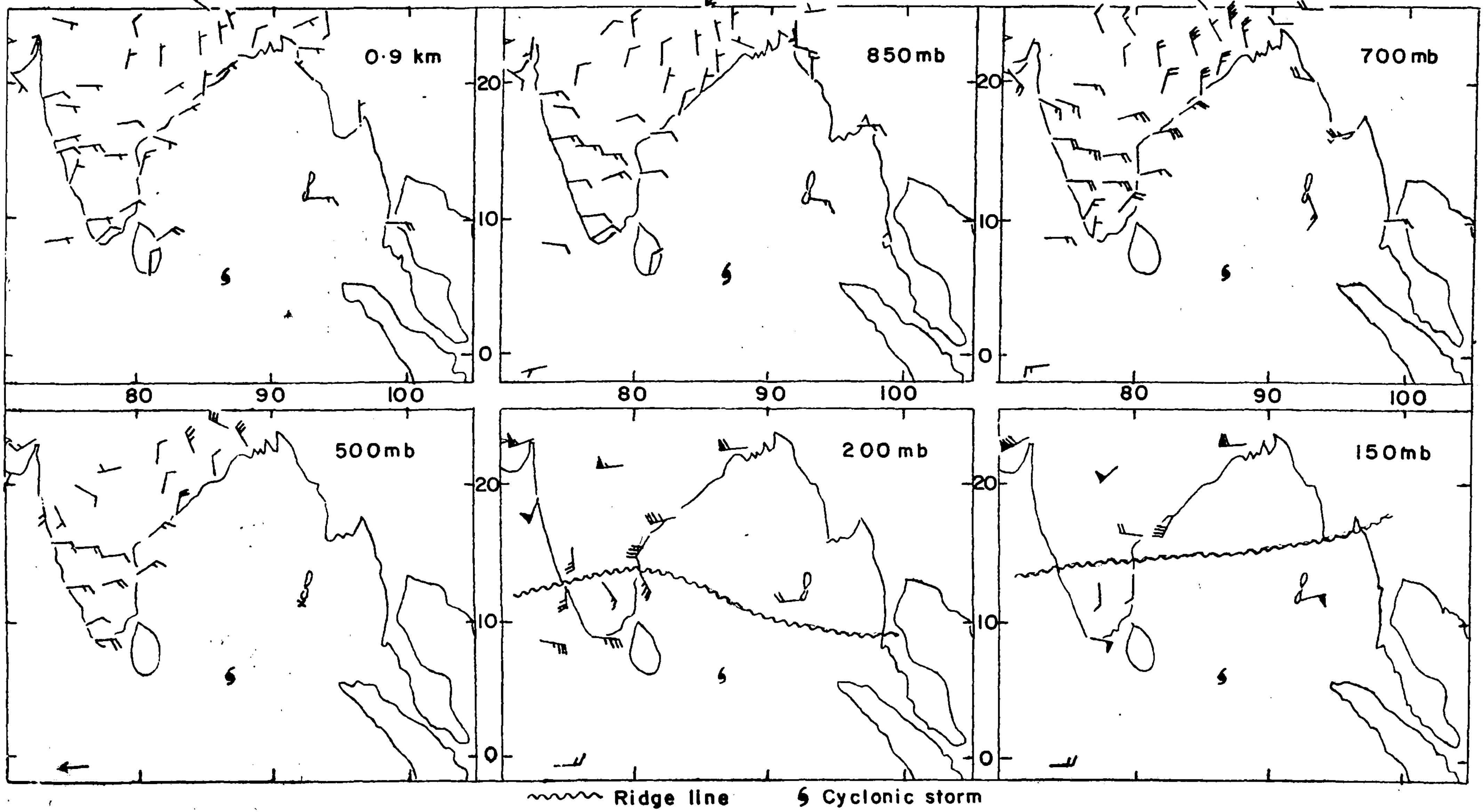


FIG. 18·9 UPPER WINDS 12 GMT 21 DEC. 64



# FIG. 18·10 SYNOPTIC CHARTS 0300 GMT 22 DEC. 64

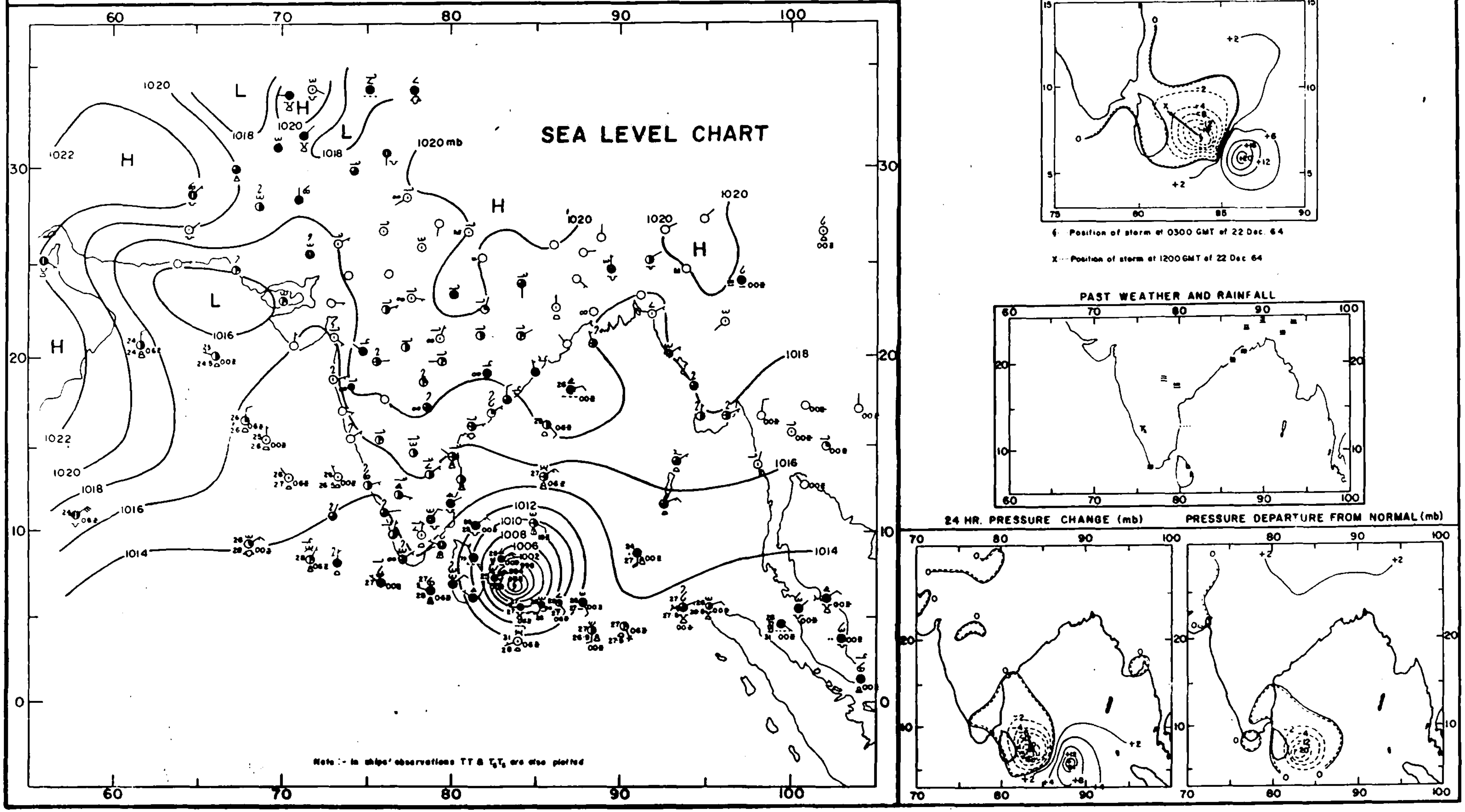
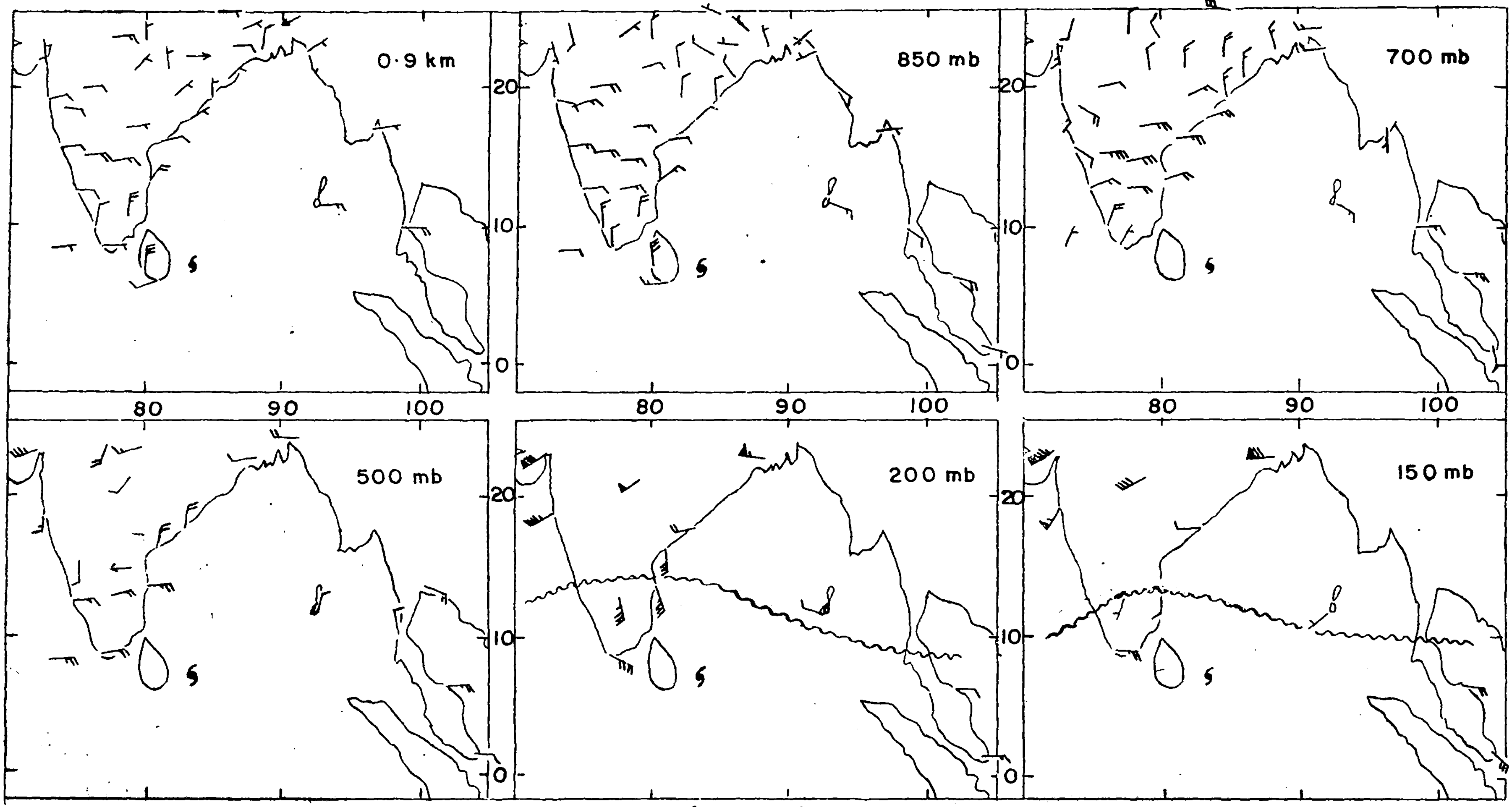
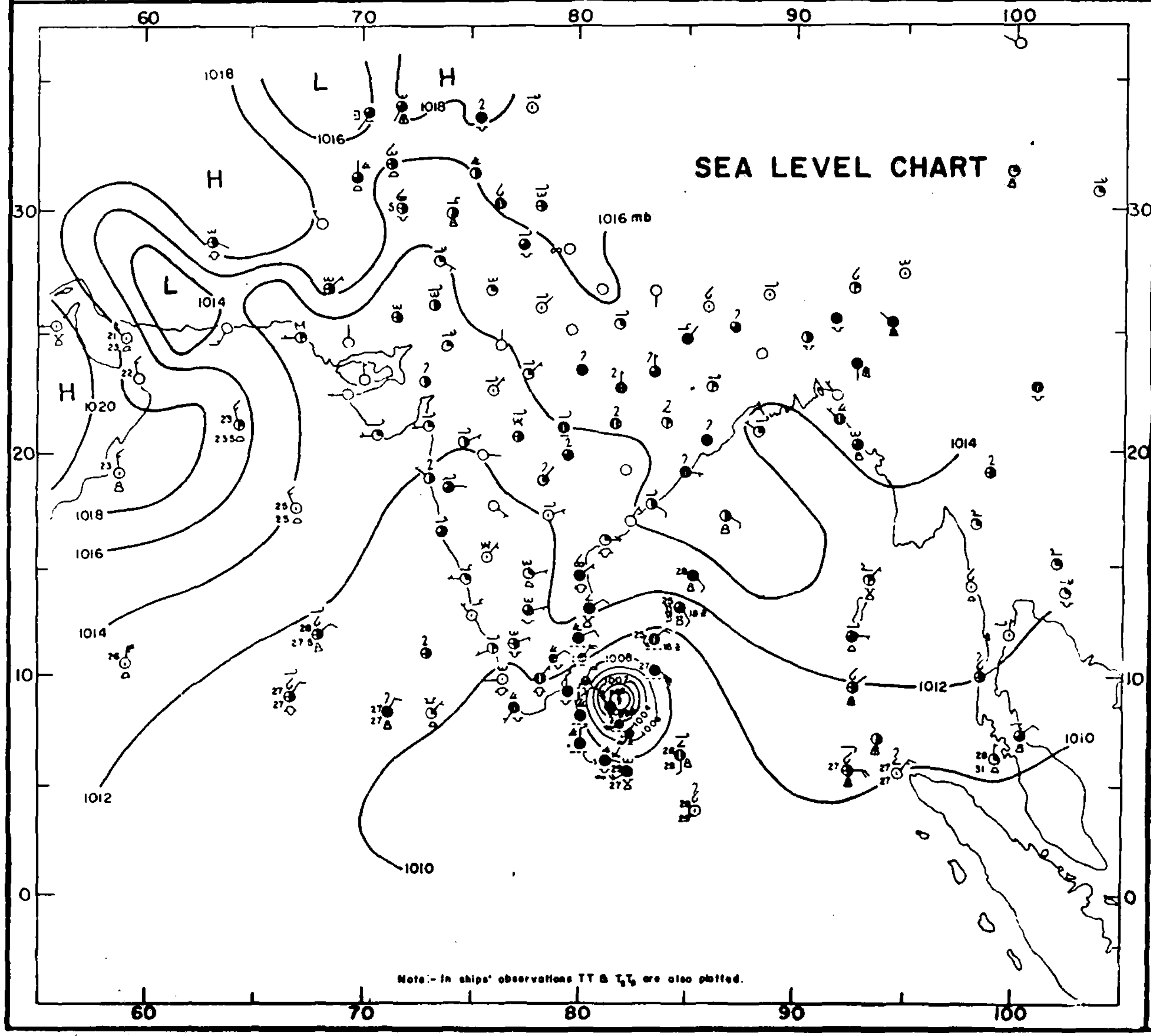


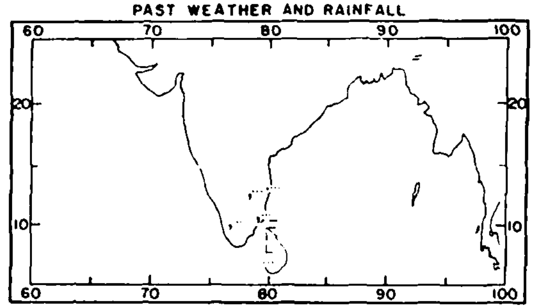
FIG. 18·11 UPPER WINDS 00GMT 22 DEC. 64

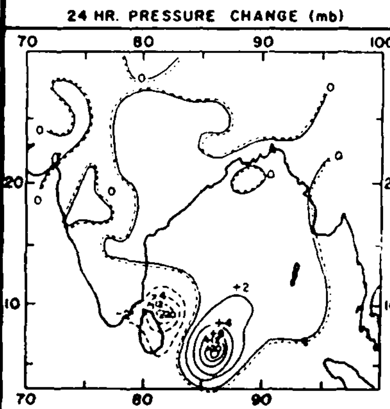



Ridge line   Cyclonic storm

# FIG. 18·12 SYNOPTIC CHARTS 1200 GMT 22 DEC. 64



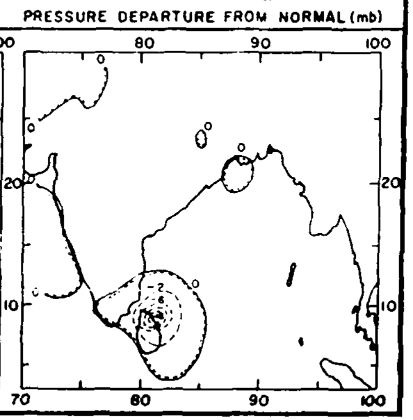
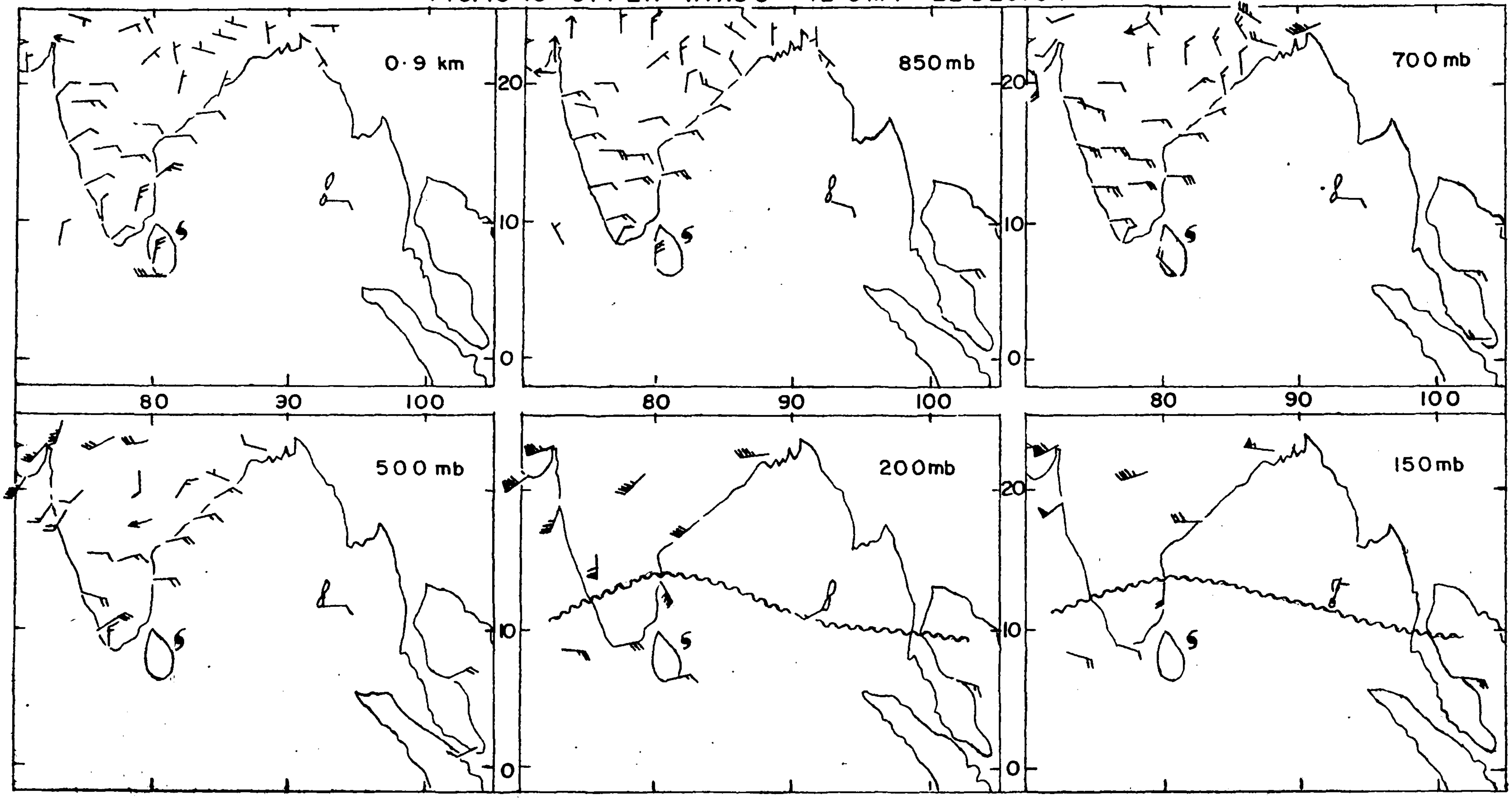



FIG. 18·13 UPPER WINDS 12 GMT 22 DEC. 64




Ridge line   Cyclonic storm

FIG. 18·14 SYNOPTIC CHARTS 0300 GMT 23 DEC. 64

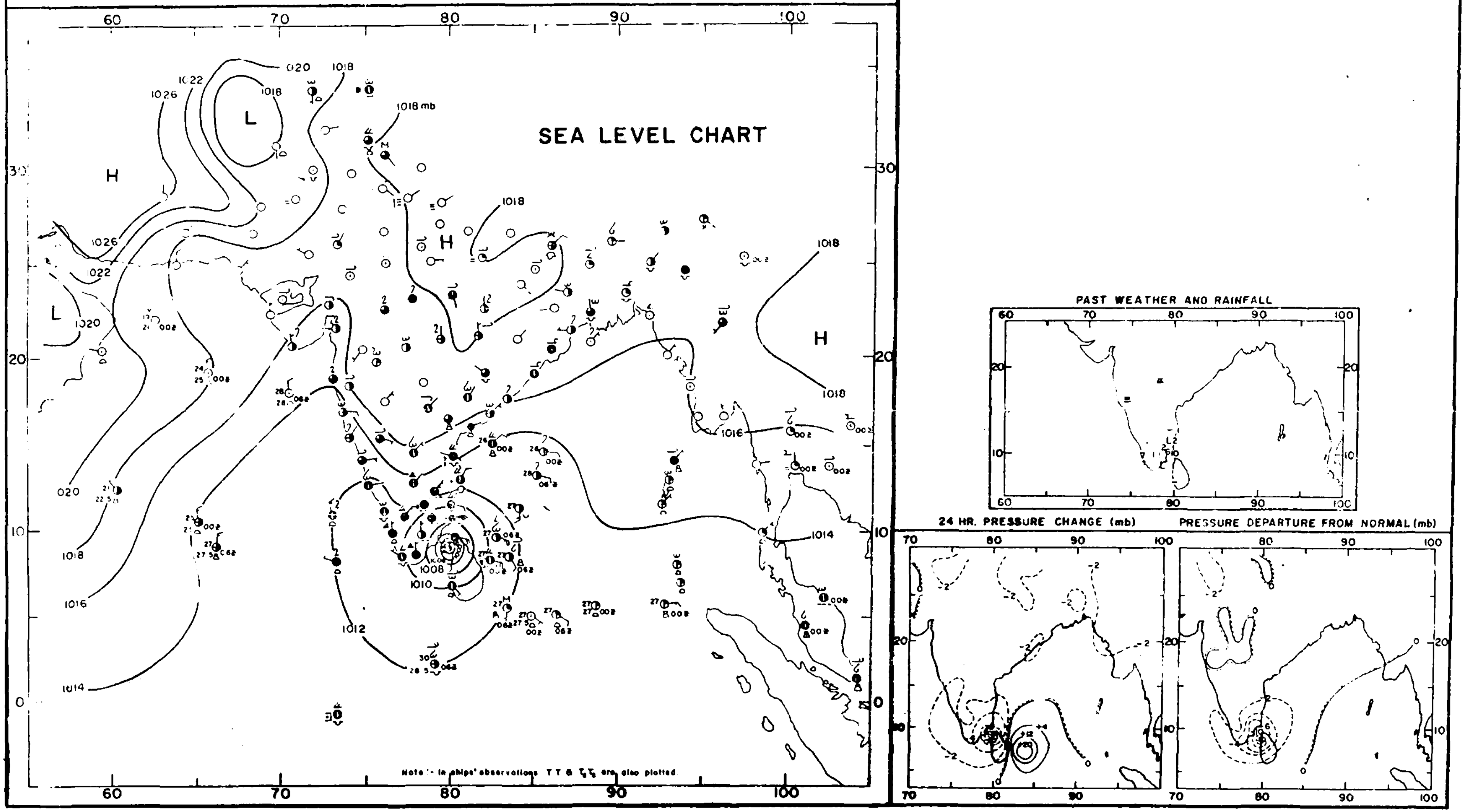


FIG. 18·15 UPPER WINDS 00 GMT 23 DEC. 64

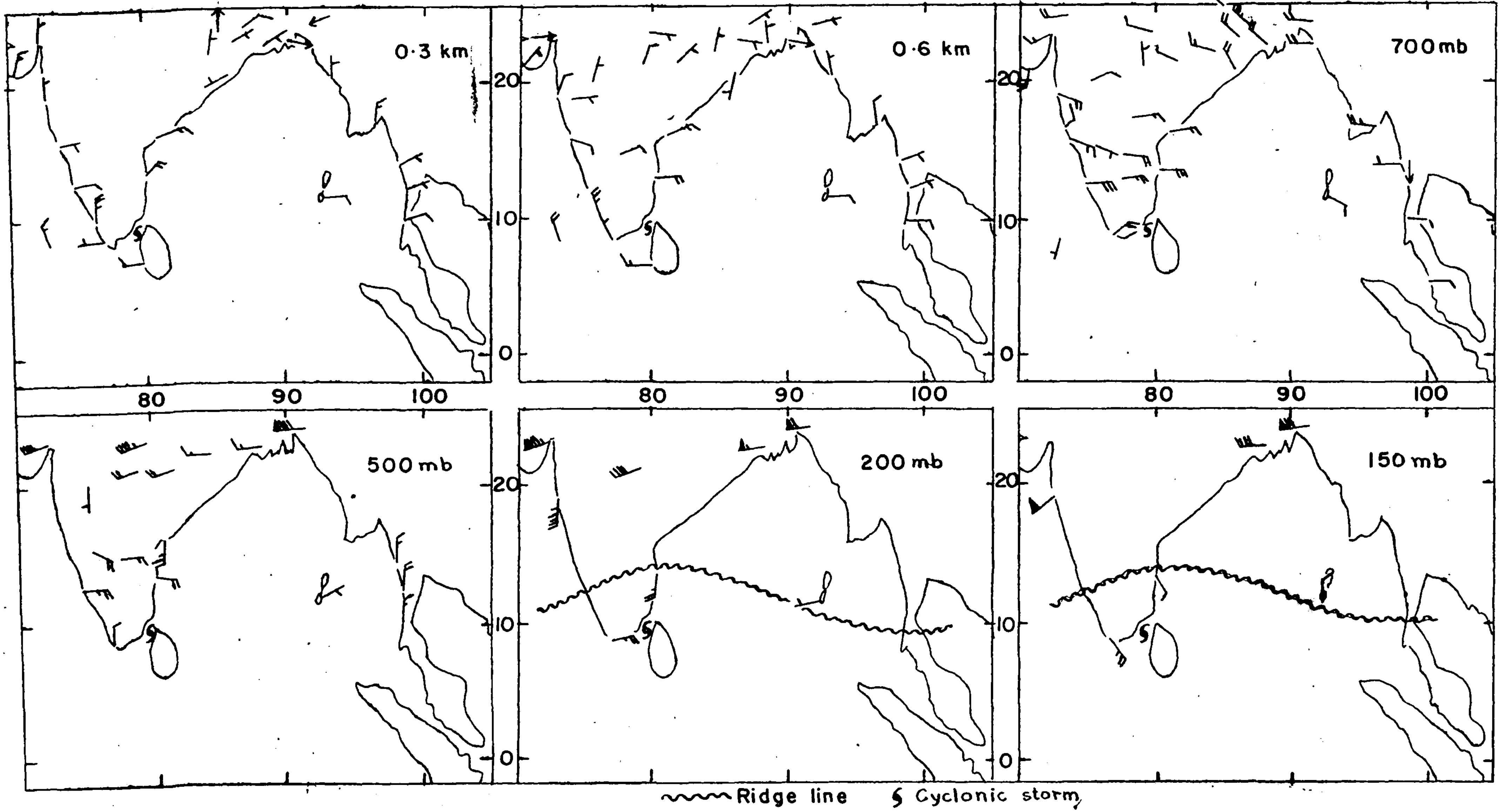


FIG. 18·16 COMPOSITE SEA SURFACE TEMPERATURE CHART (16-23 DEC. 1964)

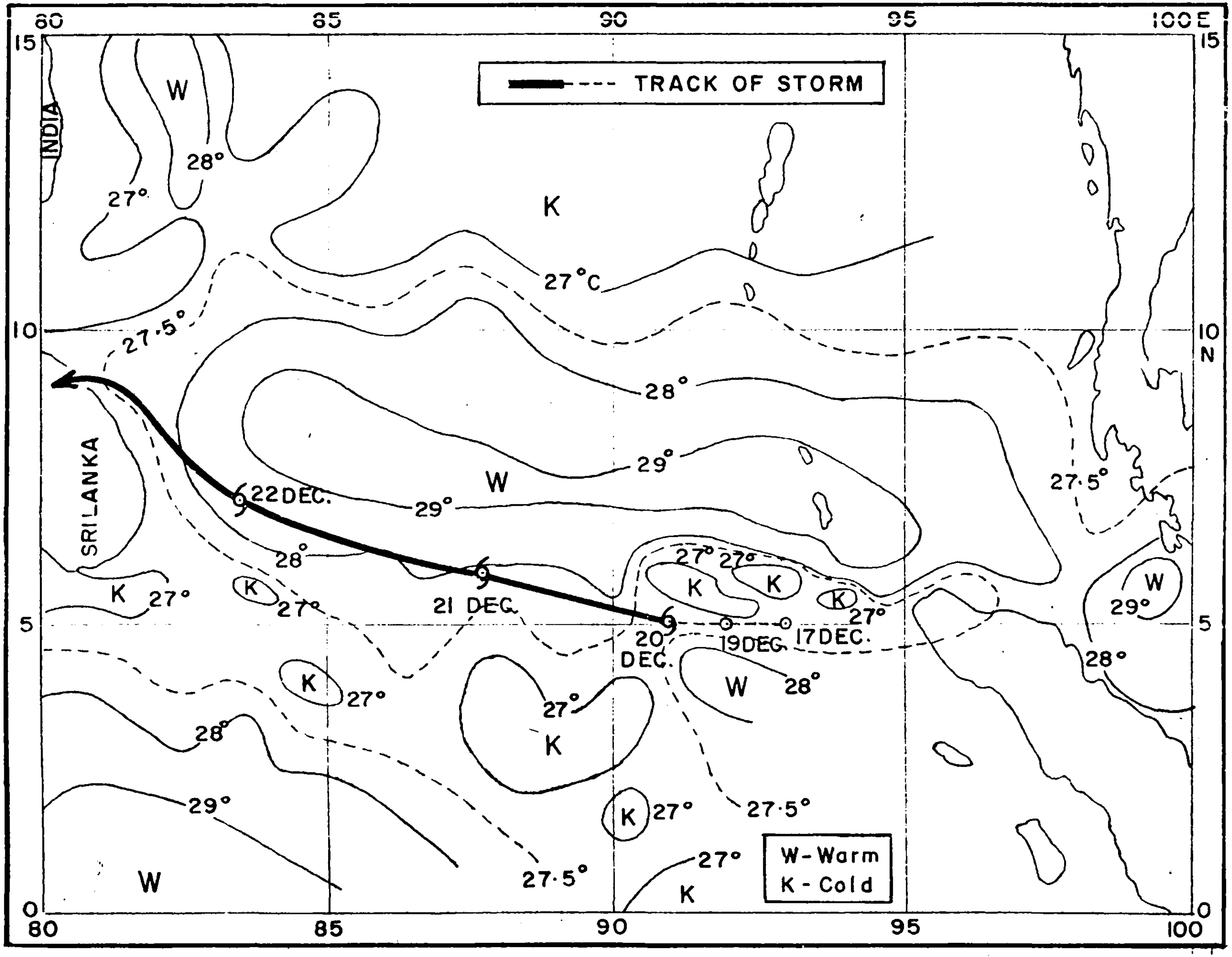
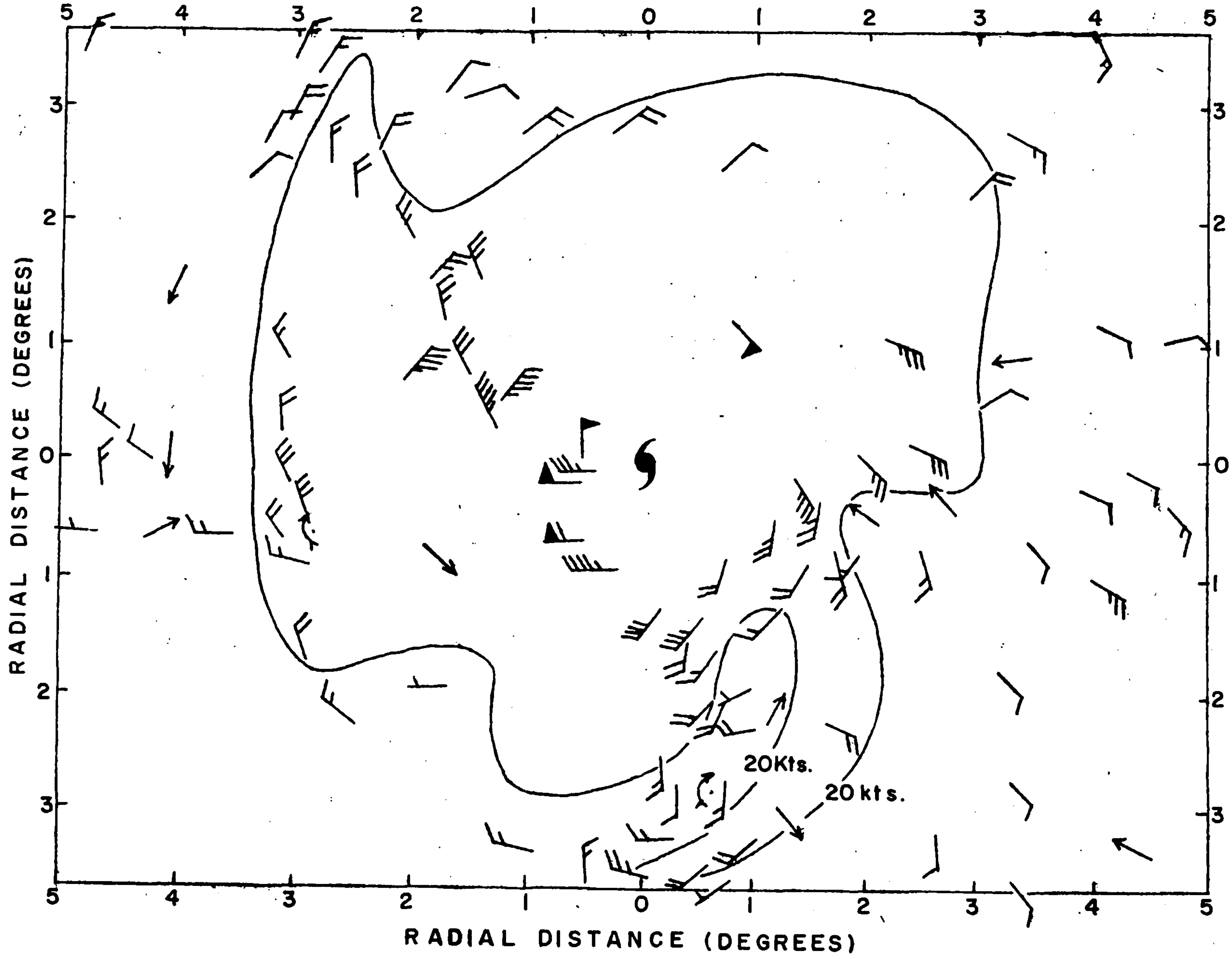


FIG. 18·17 COMPOSITE WIND CHART (21 TO 22 DECEMBER 1964)



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