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# INDIA METEOROLOGICAL DEPARTMENT

# FORECASTING MANUAL

## PART III

## DISCUSSION OF TYPICAL SYNOPTIC SITUATIONS

### 1·2 WINTER - WESTERLY JET STREAMS AND TROUGHS IN UPPER WESTERLIES

BY

GEORGE ALEXANDER AND V. SRINIVASAN

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# FORECASTING MANUAL REPORTS

| | |
|---|---|
| No. I-1 | Monthly Mean Sea Level Isobaric Charts – R. Ananthakrishnan, V. Srinivasan and A.R. Ramakrishnan. |
| No. I-2 | Climate of India – Y.P. Rao and K.S. Ramamurti. |
| No. II-1 | Methods of Analysis: 1. Map Projections for Weather Charts – K. Krishna. |
| No. II-4 | Methods of Analysis: 4. Analysis of Wind Field – R.N.Keshavamurthy |
| No. III-1.1 | Discussion of Typical Synoptic Weather Situations: Winter – Western Disturbances and their Associated Features – Y.P. Rao and V. Srinivasan. |
| No. III-2.1 | Discussion of Typical Synoptic Weather Situations: Low Pressure Areas, Depressions and Cyclonic Storms in the Indian Sea Areas during the Pre-Monsoon Season – N.M. Philip, V. Srinivasan and K. Ramamurthy. |
| No. III-2.2 | Discussion of Typical Synoptic Weather Situations: Summer : Nor'westers and Andhis and large scale convective activity over Peninsula and Central parts of the country – V. Srinivasan, K. Ramamurthy and Y.R. Nene. |
| No. III-3.1 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Active and Weak Monsoon conditions over Gujarat State – Y.P. Rao, V. Srinivasan, S. Raman and A.R. Ramakrishnan. |
| No. III-3.2 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Active and Weak Monsoon conditions over Orissa – Y.P. Rao, V. Srinivasan, A.R. Ramakrishnan and S. Raman. |
| No. III-3.3 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over Northwest India – M.S.V. Rao, V. Srinivasan and S. Raman. |
| No. III-3.4 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over Madhya Pradesh and Vidarbha – V. Srinivasan, S. Raman and S. Mukherji. |
| No. III-3.5 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over Uttar Pradesh and Bihar – V. Srinivasan, S. Raman and S. Mukherji. |
| No. III-3.6 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over West Bengal and Assam and adjacent States – V. Srinivasan, S. Raman and S. Mukherji. |
| No. III-3.7 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over Konkan and Coastal Mysore – V. Srinivasan, S. Raman, S. Mukherji and K. Ramamurthy. |
| No. III-3.8 | Discussion of Typical Synoptic Weather Situations: Southwest Monsoon: Typical Situations over Kerala and Arabian Sea Islands – V. Srinivasan, S. Mukherji and K. Ramamurthy. |

(Contd. on back cover page)

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# FORECASTING MANUAL

## Part III – Discussion of Typical Synoptic Situations : Winter

## 1.2 Westerly Jet Streams and Troughs in Upper Westerlies

by

George Alexander and V.Srinivasan

# Contents:

# 1. Introduction

1.1 During the winter months* (December to February), the westerly regime holds sway over India, particularly in the middle and upper troposphere. The subtropical ridge line at 500 mb level lies between 10°N and 15°N from Ethiopia to Vietnam, sloping southwards with height, so that over a major part of the Indian subcontinent and the Indian sea areas, the flow pattern is westerly. In other words, the middle latitude westerlies extend as far south as 15°N during the winter months. Occasionally they invade even further south so that the flow becomes westerly over the whole of India and sometimes even upto the equator. On a few rare occasions, the westerly flow may penetrate upto the equatorial regions in both the hemispheres, when we witness the phenomenon of 'pole-to-pole' westerlies which is more common in some parts of the world, as for instance in the Central Pacific, so that it is reflected even in the monthly mean charts for these areas. An example of the westerlies extending upto the equator in both the hemispheres, is given in Fig.1.1. The upper westerlies (over India) increase with height and in the upper troposphere (near 200 mb), the flow concentrates into a core of high speed which is known as the 'Sub-tropical Jet Stream' (STJ).

1.2 The westerly flow over the country is disturbed by the movement of wave perturbations from west to east and the oscillations of the jet stream. In the present report we will deal with these two features of the westerly flow over the country - viz. (i) jet stream and (ii) troughs moving from west to east.

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* Although according to departmental convention, January and February alone form the winter period, for northern India, December may also be considered as a winter month.

## 2. Westerly Jet Stream - General

2.1 The Commission for Aerology of the World Meteorological Organization (WMO), recommended the following definition for a jet stream, which has been provisionally adopted by the WMO:- "A jet stream is a strong narrow current, concentrated along a quasi-horizontal axis in the upper atmosphere or in the stratosphere, characterised by strong vertical and lateral wind shears and featuring one or more velocity maxima". For operational purposes the commission also recommended the criteria that "normally a jet stream is thousands of kilometres in length, hundreds of kilometres in width and some kilometres in depth. The vertical shear of wind is of the order 5 to 10 m/sec. per km and the lateral shear is of the order 5 m/sec per 100 km. An abitrary lower limit of 30 m/sec ( $\approx$ 60 kt) is assigned to the speed of the wind along the axis of a jet stream".

2.2 The jet stream may be thought of as a fast moving meandering current embedded in a relatively stagnant general air flow at the higher levels of the atmosphere and preserving its identity over long distances. It is, thus, a large scale feature of the upper air circulation. Another important characteristic of the jet stream is the large vertical as well as horizontal wind shear which distinguishes the high speed core from the general current.

2.3 Although the existence of strong winds at high levels has been known in a general way for a long time through occasional high level pilot balloon observations or cirrus movements, it was not until the Second World War that the study of the subject gained prominence, when the subject was suddenly pushed into the forefront by the requirements of aviation as well as the introduction of radio- and rawin-sondes as routine observational tools. Actually it was the bomber sorties over Japan by the American planes during World War II that gave the initial impetus to a study of the subject and since then a vast amount of study has been made on the subject - both observational and theoretical. The first organised study of the westerly jet stream was carried out at the University of Chicago in 1946–47 under the leadership of Rossby and Palmen, which brought out for the first time the fundamental importance of the jet stream in the general circulation as well as the day-to-day behaviour of weather systems.

2.4 An exhaustive bibliography of the literature on the subject has been compiled by the American Met. Society (Met. Abstracts and Bibliography, Vol.4 (7) – 1953). The following three publications give an excellent summary of the existing knowledge on the subject:–

i) WMO Technical Note No.19 – "Observational Characteristics of the Jet Stream (1958)"

ii) H. Riehl (1962) – "Jet Streams of the Atmosphere"

iii) E.R. Reiter (1963) – "Jet Stream Meteorology".

These publications deal with the observational aspects as well as the theories of jet streams and the relation of jet stream to weather systems and the general circulation.

2.5 It is obviously not possible to deal with the subject of jet stream in any exhaustive fashion in a report like the present one. We will, therefore, confine our attention to the westerly sub-tropical jet stream over India and neighbourhood during the winter months (December, January and February) and deal with such aspects of the subject as are relevant to the forecasters in their operational work. Accordingly, we will limit our discussions to the following aspects of the jet stream over India:–

i) Observational characteristics of the jet stream

ii) Analysis of high level charts and vertical cross-sections to locate the jet stream

iii) Jet stream in relation to weather

iv) A few typical synoptic cases of jet stream over the country

## 3. Westerly Jet Stream over India – General Features

3.1 The existence of strong westerly winds in the upper troposphere over northern India, during the winter, was known to the Indian Meteorologists for a long time. Even prior to the advent of radiosonde and rawin observations, Ramanathan and Ramakrishnan (1933 and 1939) and Venkiteshwaran (1950), from an analysis of available pibal observations, inferred the existence of strong upper westerlies over northern India during the winter months, with their maximum strength at heights of 10–12 km near about the latitudes 25°N to 27°N. Subsequently when radiosonde observations became available, Koteswaram (1953) and Koteswaram, Raman and Parthasarathy (1953) made a detailed study of the jet stream over India in winter utilising all the then available radiosonde data and brought out the main characteristics of the sub-tropical jet stream (STJ) over India. The 200 mb mean upper wind chart over India and neighbourhood for January and a vertical cross section along 80°E across the country, as given by Koteswaram in a recent paper (1969), are reproduced in Figs. 3.1 and 3.2.

3.2 The main characteristics of the sub-tropical jet stream over India in winter are:

i) The mean jet stream over the Indian sub-continent (in winter) lies near Lat. 27°N at a height of about 12 km (200 mb). The mean wind speed at the core is about 100 kts. There is a slight shift in the axis of the jet (by about 2–3 degrees of latitude) southwards as the season advances and towards end of winter or early spring, the jet stream reaches the southern-most position.

ii) From the 200 mb chart given in Fig. 3.1 as well as an examination of the mean winds at the various rawin stations along and near the mean jet axis, it will be seen that there is a slight downstream strengthening of winds (by about 10/15 kts) along the jet axis (from Jodhpur to Gauhati) across the country. The jet stream continues further north-eastwards (to the east of India) across south China, to Japan and the core speed progressively increases downstream, reaching a maximum over south Japan. At 200 mb, the mean wind at SHIONOMISAKI (Index No. 47778) in south Japan is nearly 150 kts, the highest over the area.

iii) The STJ lies entirely within the tropical troposphere about 3-4 km below the tropical tropopause. The jet is in the region of a break in the tropopause between the tropical tropopause (near 100 mb) and the middle tropopause (near 200-250 mb).

iv) The jet is caused by a concentration of the horizontal temperature gradient below the jet level and a reversal of the gradient above the jet level. At and near the jet stream level, the temperature gradient is very small or nearly zero.

v) The STJ is a very steady phenomenon and is seen practically daily on the charts during the winter, in more or less the same geographical location. The generation of the STJ was postulated by Palmen, as due to the poleward drift of air in the upper branch of the Hadley cell of the general circulation, with partially conserved absolute angular momentum. Consistent with this concept, the STJ is located near the poleward boundary of this cell. The near constancy in the latitudinal position of the circumhemispherical STJ is thus related to the constancy of the Hadley cell. Over India, the presence of the Himalayas is also believed to contribute to the stability of the geographical location of the STJ. In comparison, the Polar Front Jet (PFJ), though quite pronounced on individual day's charts, varies considerably in space and time. As a result, it is not clearly delineated on the mean charts. It is the STJ alone that is clearly pictured on the mean charts.

vi) Though the jet stream over India is generally associated with clear weather, on some occasions, there is cloudiness and rainfall (This aspect will be discussed in greater detail in Sec. 13).

# 4. Thermal and Wind Fields associated with Jet Streams

## 4.1 Temperature field

4.1.1 When there is a jet stream, there is an increase of the wind speed with height; the speed reaches a maximum at the jet level and decreases thereafter. The increase or decrease of wind with height and the existence of the jet stream are largely caused by the existence of a large meridional temperature gradient. The existence of the temperature gradient is also closely related to the presence of fronts under the jet stream. The temperature distribution associated with a jet stream is characterised by large gradients of temperature below the jet level, little or no gradient at the jet level and a reversal of thermal gradient above the jet level. The reversal in temperature may occur with or without a break in the tropopause near the jet level. In the case of the Polar Front Jet (PFJ) the 500 mb isotherms show a marked concentration under the jet axis.

4.1.2 In the case of the STJ, the large thermal gradients are usually confined to the upper troposphere. Below 500 mb, there may not be any significant temperature gradient (This aspect will be further discussed in Sec.8). Besides on account of the smaller values of the Coriolis parameter in the lower latitudes, a weaker temperature gradient than in the middle latitudes may be sufficient to produce a jet stream. The thermal structure of the jet stream will also be referred to as and when necessary in the subsequent sections while dealing the other properties of the jet stream.

4.1.3 The mean thermal properties of the STJ and PFJ are given below in a Tabular form.

## TABLE - I

Mean thermal properties of the two jet stream types

| | Sub-tropical type | Polar front type |
|---|---|---|
| T | Isotherms diverge northwards below and above the jet stream. T is almost constant both to the south and north of the jet at the jet stream level | Isotherms diverge northwards below and above the jet stream. T rises slightly to the north of the jet |
| θ | Isentropes diverge towards the south above and below the jet stream | Same as sub-tropical |
| | Nearly constant to the south and north at jet level | Greater to the north than to the south at jet level |
| $\beta$* | About 0.1°C per 100 km at the jet | Zero at the jet |
| | Positive below and negative above the jet | Positive below and negative above the jet |
| $\lvert\beta\rvert$ | Maximum at jet latitude below and above decreasing rapidly vertically through the jet | Same as sub-tropical |
| $\gamma$† | About 5°C km-1 at the jet | Zero at the jet |
| | Positive all round the jet | Positive to the south and slightly negative to the north. Positive below and above |
| $\lvert\gamma\rvert$ | Maximum at nearly the jet level to the south and decreases rapidly to the north. Decreases also vertically upwards | Maximum at the level of the jet to the south. Decreases rapidly to the north to nearly zero values. Decreases upto the jet and increases slightly above |
| $\frac{\partial\beta}{\partial y}$ | Zero at the jet stream height and latitude | Same as sub-tropical |
| $\frac{\partial\gamma}{\partial z}$ | Zero just below the jet and increases upwards through the jet. Almost 0 to the south and rapidly increases to the north | Zero at the jet, positive below and negative above. Positive to the south and negative to the north |
| $\frac{\partial\beta}{\partial z}$ | Positive maximum above the jet stream centre. Decreases to zero at about 8 km. Decreases to the south and increases to the north | Positive maximum below the jet. Decreases to zero at about 8 km. Decreases to the south and north |

* Positive when temperature decreases from south to north

† Positive when temperature decreases with height

T = Temperature; θ = Potential temperature; $\beta$ = Temperature gradient;
$\gamma$ = Lapse rate of temperature

(From "The mean Jet Stream over India and Burma in Winter" by P. Koteswaram, C.R.V. Raman and S. Parthasarathy, IJMG 1953 Vol.4, No.2, pp.111 - 122)

## 4.2 Wind Field

### 4.2.1 Vertical shear

4.2.1.1 It has already been mentioned in Sec.2 while defining a jet stream, that it is associated with strong horizontal and vertical wind shears. In the region of the jet stream, the wind direction is nearly constant with height, while the wind speed increases. The increase is small in the lower troposphere (i.e. upto 3–4 km) above which the winds increase more rapidly till the maximum strength is reached at the jet level. Above this, the speed falls off. In the mean picture, the rate of increase of speed in the mid- and upper troposphere is nearly steady although on individual occasions, the rate of increase may be very pronounced in the upper troposphere, just below the jet level, particularly in the case of a strong jet. The rate of decrease above the jet level is also well-marked upto about 16 km or so (the level of the tropopause) and thereafter the rate becomes much smaller.

4.2.1.2 The vertical profiles are sharper and more peaked when the jet stream is stronger. It has also been noticed that when the jet is stronger, the wind maxima is at a slightly lower level than when it is weaker.*
In the case of New Delhi, the variation in height of maximum winds has been (in the mean) from 11.1 km for strong jets (mean speed 163 kts) to 12.6 km for weak jets (mean speed 82 knots). The mean vertical profiles for Delhi for strong, moderate and weak jets are given in Fig. 4.1. From these profiles, it may also be seen that the rate of decrease of wind with height above the jet is slightly more than the rate of increase of wind below the jet level.

4.2.1.3 The variations of wind with height depends on the horizontal temperature gradients in the layer below. In the case of New Delhi (which is a typical station near the axis of the STJ), on an average, the wind speed drops

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* This statement requires more extensive and detailed examination.

to about half the maximum value at a level of about 4 km below the level of the maximum wind in the case of strong jets and about 6 km in the case of weak jets. Since the winds decrease at a greater rate above the level of the maximum winds, the corresponding height values where 50% of the maximum values are reached are slightly less.

### 4.2.2 Horizontal shear

4.2.2.1 The jet stream has not only a strong vertical shear but it has also a strong horizontal shear. According to the definition of a jet stream, the horizontal shear should be at least 5 m/sec per 100 km (i.e.) about 10 kts per degree of latitude in our region. The lateral shear is not the same on either side of the jet stream; it is considerably stronger on the cyclonic than on the anticyclonic side. In a rough way we may say at the jet level, the speed drops to half the value at the core in about 4° of latitude to the north and in about 7° of latitude to the south. The maximum shears are found at or near the level of the jet stream (viz. near 200 mb over our country). The shears also decrease as we move away, from the axis of the jet stream. Over India, in the mean, at 200 mb level the shear falls to half the value at the core, about 7° degrees of latitude both in the north and in the south. Examples of wind profiles across India in the case of a strong and a weak jet stream are given in Fig. 4.2.

4.2.2.2 While there is no theoretical limit to the magnitude of the shear on the cyclonic side (shear values as high as five times the Coriolis parameter havebeen reported), its magnitude on the anticyclonic side is limited by the criterion that the absolute vorticity cannot become negative. Thus, in a straight jet stream, the maximum anticyclonic shear at 100–300 km from the jet axis has about the value as the Coriolis parameter at those latitudes. The limiting values of the shear in the Indian latitudes are:-

| Lat. | Coriolis parameter ($10^{-4}$ sec$^{-1}$) | Limiting value of shear on the anticyclonic side (Kts/deg. of lat.) |
|---|---|---|
| 15 | 0.3775 | 7 |
| 20 | 0.4988 | 10 |
| 25 | 0.6164 | 12 |
| 30 | 0.7292 | 14 |
| 35 | 0.8365 | 16 |
| 40 | 0.9375 | 18 |

The isotachs on the anticyclonic side, therefore, should be so spaced that these limiting values of shear are normally not exceeded.

4.2.2.3 Based on a study of upper tropospheric winds over India, Pisharoty et. al. (1957) suggested horizontal shear values of about 0.9 time the Coriolis parameter appropriate to the latitude (particularly in winter) for interpolating wind values to the south of the jet stream. In a study of jet stream over India during the period 1-15 Feb. 1967, Singh (1971) reported a maximum anticyclonic shear of about 12-13 kts per degree latitude, and a maximum cyclonic shear of about 20 kts per degree of latitude.

4.2.2.4 If the jet has a well-marked curvature, the curvature term has also to be taken into account. in determining the absolute vorticity. The anticyclonic shear can be stronger than the Coriolis parameter for cyclonically curved jet stream and weaker in the case of anticyclonically curved jet. In the case of the cyclonically curved jet, the anticyclonic shear to the south of the jet axis may be even as much as double the Coriolis parameter.

4.2.2.5 In view of the operational necessity to estimate the core speed of the jet, many attempts have been made to estimate the shape of the wind profile on either side of the jet axis so that the core speed can be estimated from peripheral wind observations on either side of the jet. Some of the methods will be described below. In view of the large variety of the profiles, these methods can only be treated as rough guides.

i) We have already referred to the suggestion for applying horizontal wind shears of value 0.9 f, to interpolate wind values on the anticyclonic side.

ii) Assuming a straight line profile on either side of the jet, Reiter has shown in the case of strong jet stream, that on the cyclonic side, the core speed is about 3 to 4 times the speed over a station at a distance of about 300 km from the jet axis and on the anticyclonic side it is only about 2 times.

iii) J.J. George has given a nomogram to estimate the wind at the jet core, utilising a wind observation adjacent and to the right of the core (Fig. 4.3).

iv) Fawcett E.B. and Snellman L.W. (1959) have given a graphical method for estimating the position and strength of the core of maximum winds on a constant pressure level, in between two radiosonde stations located 4 to 9 degrees of latitude apart, by computing the mean gradient wind between the two stations and drawing the estimated horizontal wind profile. The method as slightly amended, is illustrated below.

Suppose we infer that the maximum wind is located between two stations A and B for which data (contour heights) are available for 200/250 mb level. The mean geostrophic wind (gradient wind if the contours are curved) between the two stations A and B is calculated and plotted as in Fig. 4.4. Points A and B in the diagram (plotted against their appropriate latitudes) represent the wind speeds (at 200/250 mb levels as the case may be) at these two stations (Station A is to south of the jet axis). PQ is the ordinate along the mean geostrophic/gradient wind between A and B as computed from the contour heights at A and B. The jet axis is somewhere between A and B. From considerations of continuity with previous charts and inspection of nearby wind reports a first guess of central speed at the core is made. Let the guess value be x kts. Draw a line through A whose slope represents the average anticyclonic shear to the south of the jet core. The average anticyclonic shear is assumed to be 10% of the core speed per degree of latitude. The slope is then worked out from the guess value x. Let A C be the line whose slope represents the average shear to the south of the jet axis. A C cuts P Q at T. From B draw a line B S D to cut AC at D and PQ at S such that

$$\Delta\,DST = \Delta\,BQS + \Delta\,APT ,$$

The curve ADB represents the horizontal wind profile at this particular pressure level between the two stations A and B. The point D represents the core speed and the latitude at which the core lies. The authors have mentioned that to get reliable values by this method, the distance between stations A and B should be between 4 to 9 degrees of latitude and that the mean wind between A and B computed when the contours are anticyclonically curved are not reliable.

These methods (i) and to (iv) are only rough guides. Besides they also require verification over Indian area on operational basis. It may also be noted that the shears – both horizontal and vertical – vary along the axis of the jet stream and also with time.

## 5. Location of the Position of the Jet Stream

5.1 An important part of the analysis of the upper air charts is to locate the position of the jet stream. The axis of the jet stream is identified on the horizontal charts as the line (straight or curved) along which the wind speeds are the highest. Since the core of the STJ over India is near about 200 mb, constant pressure charts for 250 and 200 mb levels are the basic charts to locate the jet stream. This has to be supplemented by the analysis of thermal patterns at levels below (viz. 500 to 300 mb). Space sections across the country along some selected longitudes, as well as vertical time-sections of some key stations provide the necessary auxiliary material. The cross section charts provide the information regarding the height of the jet core. The satellite cloud patterns also give indications of the location of the jet.

## Constant Pressure Charts

5.2 The charts for 250 and 200 mb levels are basic for the location of the jet stream. Where wind observations are available, the line of maximum wind speeds is the axis of the jet stream. The rawin observations at these levels may be supplemented by pibal winds, reports from aircraft and satellite-derived upper winds. But while using these additional data, it should be remembered that they may not strictly pertain to the 250 mb or 200 mb levels and each type of data has its own limitation. Even over areas where the network of rawin observations is sufficient for streamline analysis, it is often found that a reliable isotach pattern cannot be had with these observations alone. Over oceanic areas and data sparse regions, aircraft reports and satellite data are the only observations available.

5.3 While wind direction is more or less constant through a fairly deep layer in the upper westerlies, the speeds may differ considerably even through a small layer, since the vertical wind shears are large near the jet level. While considering the individual observations, it should be borne in mind that at these high levels the wind speeds as reported may be in error by as much as 10%. That is, if a station has reported a speed of 100 kts the accurate value may range anywhere between 90 kts and 110 kts. Hence certain amount of smoothing is necessary while drawing the isotachs. Besides, if the reported wind observation is the last height reached or very close to the last height, the speed may be abnormally high and hence such observations have to be rejected. These limitations should be borne in mind while drawing the isotachs and locating the jet axis. Similarly the properties of the wind field near the jet stream discussed in the different sections of this report should also be taken note of while doing the isotach analysis.

5.4 When sufficient wind observations are not available, one may utilise winds derived from the contour charts to draw the isotach patterns. However, the computed winds are the average winds over a latitudinal distance and hence can be an under-estimate of the actual winds. Besides a computed wind can be in large error, if it is calculated over short distances. In this connection it is important to note that "it is a rather delicate task to draw the high level contours since, contrary to earlier beliefs, their spacing is far from linear. Indeed, a great deal depends on proper non-linear spacing of contours". (Riehl, et.al., Met. Monograph No.5, p. 72)

5.5 Experience shows that wind observations are generally more reliable than either temperatures or geopotentials. Hence wind observations should form the primary criterion to determine the jet core, wherever such observations are available.

5.6 Since the vertical time-sections show that the high speed isotachs around the jet core extend downwards (in an elliptical form) through fairly deep layers, even the wind distribution in levels below 200/250, viz. upto 500 mb, can give a rough idea of the location of the jet axis. However, it should be remembered that in the case of the STJ, the vertical depth is relatively small and the high speed winds associated with the jet are often confined to a shallow layer near the jet core – hardly perceptible below 300 mb.

5.7 But in some cases, the winds even at 500 mb level are quite strong, indicative of a jet stream above. This is usually so in the case of a strong jet, as may be noticed even in the mean profiles for New Delhi given in Fig.4.1. A difficulty in locating the jet by noting the strong winds at levels other than where the jet core is situated is the layered structure of the STJ as will be discussed subsequently in Sec.7.

5.8 The concentration of the wind flow into a jet is uniquely related to the horizontal temperature gradients in the layers below. Because of the strong temperature gradient, the winds increase with height upto the jet level, the increase being quite high in the upper troposphere within about 2 km of the jet core. Hence, the thermal and thickness gradients in the levels below the jet core (viz. in the levels between 500 and 300 mb levels) should be quite large in the latitudinal belt where the jet core is located. There should be a packing of thickness lines/isotherms in this latitudinal belt and away from this region, the spacing should spread out. Thus, the isotach analysis at 200 mb and 250 mb levels should be consistent with the thermal/thickness patterns below.

5.9 It may also be possible to obtain some empirical relations between the locations of the jet core and the temperature values just below the core on a regional basis.

5.10 The jet stream usually tends to follow the streamline/contour. This is particularly so when the speed does not vary much along the axis. However, when the speed varies appreciably along the axis, the jet axis may cross the contour/streamline. The axis tends to cross towards the higher contours when the speeds are decreasing downstream(i.e. where the air is decelerating) and towards lower contours where the speeds increase along the axis (i.e. where air is accelerating). This feature is generally well-marked when a jet stream is embedded in a trough-ridge pattern as will be explained in the next paragraph. For an example of the cross contour flow of the jet stream, refer to the case history discussed in Sec. 31. In this case, when the deep trough was extending from Afghanistan to East Central Arabian Sea off Maharashtra coast (on 11 January 1971 1200 Z) the sub-tropical jet was running from North Konkan to East Tibet and west China with a marked down-gradient cross contour flow. More instances are available in the discussion of other typical situations also. Over Japan where even in the mean there is a strengthening of the winds downstream along the jet axis, a mean cross contour flow of 8.5 m/sec directed towards the lower contours has been noticed (Mohri, 1953).

5.11 When the jet stream is associated with a well-marked trough-ridge pattern of upper air flow, the meandering of the jet stream along the wave is very striking, though the jet axis may not be strictly parallel to the streamline/contour pattern. A typical case of a meandering jet is given in Fig. 5.1 which depicts the situation on 20 January 1973. On this day, there were three major troughs – one over central Mediterranean, the second over Afghanistan, Pakistan and north Arabian Sea and third off the China coast. In unison with these three troughs, the axis of the STJ also executed a sinusoidal wave pattern.

5.12 In a progressive wave trough with uniform wind speed along the jet axis, the jet axis has usually a greater amplitude than the streamline/contour pattern. If the wind speed also varies along the jet axis, the effect discussed in para 5.10 will become additive. Thus the deviations of the jet axis from the streamline/contour patterns can occur either because of a large amplitude wave trough or variations in wind speed along the jet axis or both. The jet core is at a slightly lower height in the troughs than in the ridges.

### Vertical Cross-sections

5.13 Vertical cross-section is a standard auxiliary tool to aid the analysis of charts on the horizontal plane. A vertical cross section provides the analyst with a three dimensional picture of the wind system, which is rather difficult to obtain from the horizontal charts (in the x-y plane). The analysis of the cross-sections is also relatively simpler and more objective, than the analysis of horizontal charts. Besides, the cross section enables the analyst to interpolate between observations and obtain the interpolated values to fill in the data void regions.

### Time cross-sections

5.14 Time cross sections of key stations lying in the region of the jet stream are useful to fix the position of the core of jet stream in three-dimension. They indicate the height at which the jet core is located and also any latitudinal shift of the jet core. Movement of wind maxima along the jet axis can also be traced from the time-sections of stations along the jet stream.

## Space Cross Sections

5.15 Space cross sections along selected longitudes are very useful to locate the jet stream in three-dimension and study its day-to-day behaviour. Space cross sections are extensively used in studies of jet stream. In so far as India is concerned, cross-sections along two mean longitudes which cover a fair density of stations are suggested. They are:

i) along a mean longitude of 75°E containing stations within 3 to 5 of longitude from this meridian (75°E) from Russian Turkistan (Alma Atta, Tashkent etc.) in the north to Lakshadweep and Maldives in the south (Minicoy, Trivandrum, Colombo and Gan);

ii) along a mean longitude of 90°E from East Tibet in the north to Bay Islands in the south.

Examples of typical time and space cross sections are given in Fig. 5.2 and 5.3.

5.16 An important point to be borne in mind in the analysis is, that in space cross sections, the horizontal and vertical scales are highly disproportionate. While in the vertical, the extent is about 20 kms or so, in the horizontal, the sections may cover about 2000 kms, thus leading to a ratio of 1:100 between the vertical and the horizontal axes.

## Horizontal Profiles

5.17 When time does not permit the preparation of daily space sections, a north-south horizontal wind profile at one or two standard levels near the jet stream core may provide useful supplementary information to fix the jet stream position. For instance, in our country horizontal wind profiles along 75°E and 90°E at 200 mb and 250 mb levels may be prepared. If 00Z and 12Z as well as 200 mb and 250 mb data are all plotted on the same diagram, the analyst can draw smooth profiles maintaining space and time continuity. For a typical day's profile along 75°E refer to Fig. 4.2.

## Cross-Section of Temperature anomalies

5.18 Riehl has suggested that a vertical cross section of temperature anamolies (from some mean value, usually with respect to the mean sounding computed from all the soundings in the cross sections) along a longitude may be useful to locate the jet stream with a fair degree of confidence. The jet core is located in the 'Col' region between two warm and two cold anomaly regions. An example of the mean temperature anomaly cross section across India is given in Fig.5.4 (Jan. 1968).A Typical day's anomaly chart is also shown in Fig.5.5.

## Tephigrams

5.19 Since the core of the jet stream is most often in between two standard pressure levels, it may not be possible to locate the level of the jet from the analysis of charts for standard pressure levels. The jet core level may be interpolated from the levels of maximum winds reported by stations in the neighbourhood or from cross-section analysis. Where such winds or cross sections are not available - but radiosonde observations are available on either side of the jet axis - we may utilise the property that at the jet level the temperature gradient is a minimum (or zero) and obtain the level of the jet core as the level where the two ascent curves meet. Where more than two radiosonde observations are available, a mean level may be taken if all the curves do not cut at the same level. This may also be utilised as a cross check on the analysis of the wind field ( particularly in a cross section ) to determine the jet core. Bielinski (1960) has outlined a method of even locating the jet maxima along the jet axis by using a number of pairs of ascents on either side of the jet axis.

5.20 As an example, the tephigrams of Srinagar, New Delhi and Nagpur for 0000 GMT of 22 January 1968 are given in Fig. 5.6. The curves meet near about

200 mb. Actual winds also show that the jet axis is located near 200 mb. between Delhi and Nagpur. Note (i) the temperature gradient reverses sign above 200 mb level (ii) in the layers below the jet level, the maximum difference in temperatures between Delhi and Nagpur is at 400 mb, which is nearly double the value at 700 and 600 mb level, implying that the STJ is created by the temperature gradients mainly in the mid-troposphere (refer to Sec.8 for further discussion on this point).

## 6. Wind Maxima

6.1 It is usually seen that the wind speeds along the jet axis are not uniform but they vary. The isotach patterns show high speed centres along the jet axis with relatively weaker winds in between. The isotach maxima are also referred to as 'jet streaks' by some authors. The wind maxima (or speed maxima) travel along the jet axis, but the speed of travel is highly variable and is much less compared to the speed of the general wind flow in which these maxima are embedded. Speeds of travel from 0 to 25 or 30 kts have been reported. High speed isotachs are elliptical in shape and are generally parallel to the contours or streamlines.

6.2 To a considerable extent, the wind maxima retain their central speeds, though occasionally they may weaken or strengthen during their travel downstream. In the Indian latitudes, the high speed centres at and near the jet levels usually have a range of values between 100 and 140 kts, although in extreme cases, the central speed may reach even 200 kts. Higher speeds are more common in February than in December or January.

6.3 Isotach patterns delineating the wind maxima are of variable sizes. It has been observed that the pattern sizes are related to the central speed and isotach patterns of greatest length and breadth are those with the highest speeds. The lengths of the isotach patterns of jet maxima at a given latitude are on the average, proportional to the wind speed and for a given wind speed are greater in low than in high latitudes. If we arbitrarily fix the lateral dimension ($W_J$) of a wind isotach pattern as the distance between points on either side of the jet stream core where the wind speed reaches half the value at the core, and length ($L_J$) of the isotach pattern as the distance between the points where the minimum wind speeds ($V_{Min}$) are reached along the jet axis, the length to the width ratio is given by

$$\frac{L_J}{W_J} = \frac{4\pi\bar{V}}{V_M}$$

where $V_M$ is the maximum wind at the centre of the isotach pattern and $\bar{V}$ is the mean wind along the jet axis i.e. $\bar{V} = \frac{1}{2}(V_{max} + V_{min})$. Over north America, it has been found that the length is usually about ten times the width.

6.4 When the jet axis is of a wave form, the high speed centres (or wind maxima) are located over or near ridge, rather than at the trough, though high speed centres at the trough are not ruled out. This feature of the location of the wind maxima at the crest of the wave is more prominent in STJ than in PFJ. On many occasions, with the wind maxima located at ~~the~~ two consecutive ridges, the jet stream may even be discontinuous across the trough in between the two ridges. Shears are often the strongest upstream from the wind maximum. The 200 mb chart for 28 January 1973 (0000 Z) is given in Fig. 6.1 to illustrate the location of a jet maximum at the ridge and a minimum at the trough. On this day, a pronounced maximum reaching 200 kts was over East Tibet and Central ~~West~~ China, over the ridge. Further west, over Western India, where the trough was located, the highest speed along the jet was hardly 100 kts. Thus there was a strengthening by nearly 100 kts between the trough and the ridge. The 200 mb chart for 23.12.69 given in the Sec.30 is another example where the wind maxima are over the crests of the wave and the minimum is at the trough. In this case the STJ is almost discontinuous at the trough.

6.5 The wind speeds reported at the various standard levels have certain inherent 'noise' mixed up which cannot be filtered out. Any isotach analysis done with the wind speeds reported as such, will, therefore, show a number of jet fingers and fail to bring out the main jet axis and the core or the wind maxima. While 'jet fingers' may be a genuine feature of the upper air flow on some occasions, more often than not, they are spurious, introduced by inaccuracies in wind observations. Where the jet is strong, these inaccuracies in the wind speed may not obscure the main features of the wind flow. However, when the jet is not strong, the spurious noise may lead to an isotach analysis exhibiting a number of jet fingers which may or may not be genuine. Hence a good smoothening of wind speed field is necessary while doing the isotach analysis. As mentioned earlier in para 5.3 a smoothening of wind speeds by about 10% (or sometimes even 15%) of the reported values is permissible. The smoothening together with space and time continuity will enable the analyst to draw stable and reliable isotach patterns and place the jet axis with a fair degree of accuracy and objectivity. In order to smoothen out the unrepresentative wind fluctuations more objectively and systematically, Reiter introduced a technique of "Layer of Maximum Wind (LMW)" charts which will be discussed in Sec. 10.

## 7. Layered Structure of the STJ

7.1 Analysing the structure of the STJ over USA, Newton and Persson (1962) noticed the following features:-

i) There are often two layers of maximum wind to the south of the jet core. The upper layer is nearly horizontal or slightly sloping upwards to the south, whereas the lower layer shows a well defined slope southwards with height, lying nearly on an isentropic surface.

ii) On any particular occasion either of the layers may be more prominent.

iii) The surface of maximum wind rises to the north of the STJ core, and this layer of maximum wind may extend in a continuous fashion as far northwards as the PFJ.

The model of STJ structure postulated by Newton and Persson is given in Fig. 7.1. Such a layered structure has been noticed (Singh 1971, Misra 1973), in the Indian latitudes also and the upper layer is reported to be more prominent than the lower one.

7.2 In view of the layered structure, the fixing of the position of the axis of the jet stream by an analysis of constant pressure charts at one or two levels only, may lead to erroneous inferences. It is, therefore, necessary to visualise the three dimensional structure by the analysis of a few more levels (in addition to the 200/250 mb level) and also cross-section charts, to dilineate the axis of the jet unambiguously.

7.3 An analysis of the maximum wind data for the Indian stations during the six year period (1968-73) also lends support to the layered structure of the STJ. While over Delhi the frequency distribution of heights at which the maximum winds occur, shows a single peak near 11.5 km, stations further south such as Jodhpur, Gwalior and Ahmedabad show a double peak which may be interpreted to be indicative of the two layered structure of the STJ. It also appears that while the upper layer of maximum wind south of the STJ core may extend much further south (a distance of as much as 15 degrees of lat.) the lower layer of maximum wind extends to a shorter distance only (8 to 10 degrees of lat.).

## 8. Sub-Tropical Front

8.1 The Polar Front Jet (PFJ) is usually, though not always, associated with a frontal system in the lower troposphere. The frontal system may also extend throughout the whole depth of the troposphere. On the average, the jet stream is located near about the intersection of the frontal layer with the 500 mb surface. The approximate location of the polar front jet can, therefore, be inferred from the isotherm packing at the 500 mb surface corresponding to the frontal layer. The frontal system may not be present along the entire length of the jet stream.

8.2 In the case of STJ the thermal gradient (baroclinic zone) is present only in the mid- and upper troposphere, while the lower troposphere may be quasi-barotropic. This baroclinic zone in the mid and upper troposphere associated with the STJ is called the 'jet stream front' or the "sub-tropical front" (STF). This front is seen mainly above 500 mb level. Some times the STF can be as intense as a Polar Front. The STF usually extends southwards on the anticyclonic flank of the jet stream. In the mean, it has a thickness of about 3 km in the north and reduces to about 1 km at the southern end.

8.3 An example of the concentration of the thermal gradient in the upper troposphere in the case of the STJ is given in Fig. 8.1. The temperature gradient in the latitudinal belt between Jodhpur and Delhi where the STJ is located, increases as we go upwards from 600 mb; the gradient is very pronounced at 300 mb (just below the jet core) and it changes sign at 200 mb level (above the jet level).

## 9. Tropopause Structure near the Jet Stream

9.1 The types of tropopause that occur in the atmosphere are broadly divided into three classes and the classification depends upon the heights at which the tropopauses occur and the latitudes where they are found. The three types are:-

i) Polar Tropopause - This is usually noticed near 300 mb level poleward of Lat. 45° to 55°

ii) Tropical Tropopause - This is usually near 100 mb level and extends from the equatorial region poleward to 35° or 40° of lat.

iii) Middle Tropopause - which occurs near about 200 mb level in the region between Polar and Tropical Tropopauses. The PFJ is found at the southern end of the polar tropopause, just at the break in the tropopause. Similarly the STJ is found in the region of the break between the middle tropopause and the tropical tropopause. The middle tropopause extends southwards to form the base of the jet stream front of the STJ.

9.2 In the Indian area, we find

i) the tropical tropopause extends over the whole country at an average height of 16.5 km – upto 23°N and lowers by about 0.5 km towards the extreme north of the country. This tropopause is characterised by an inversion at the base of the stratosphere.

ii) The middle tropopause occurs over the extreme north of the country at an average height of about 11.5 km and a temperature of about – 54°C. It is characterised by a nearly isothermal layer, above which the second tropopause (the tropical tropopause) may occur. It may be noticed over north India extending as far south as 23° to 25°N. The middle tropopause (between 10 km and 12 km) is noticed at Srinagar on nearly 50% of the occasions in winter (December, January and February) while over Delhi and Jodhpur it is seen only on 15% to 20% of the occasions. Over the other stations in north India, the appearance of this tropopause is only on a very small number of occasions.

iii) The polar tropopause is generally outside the country and may be seen over Srinagar occasionally when the polar air incursion takes place into the country.

A model diagram showing the tropopause structure in relation to the jet stream is given in Fig. 9.1.

## 10. Analysis of the Layer of Maximum Wind

10.1 The large fluctuations in wind speeds near the jet stream and the necessity to smoothen the values while drawing the isotachs have already been referred to in Sec. 6. In order to filter out errors in wind measurements and unrepresentative wind fluctuations and get a stable pattern of wind speed distribution in the jet stream region, Reiter developed a technique of layer of maximum wind charts, which gives the integrated picture of the wind over a limited depth centred on the jet core. This technique enables the analyst to bring out a simple picture of the three dimensional wind flow and follow its space and time continuity.

## Layer of maximum wind

10.2 The layer of maximum wind (LMW) is determined for each rawin ascent, by constructing a smoothened vertical profile of the wind. The mean wind speed of the LMW is defined as 90% of the maximum wind speed of the vertical profile. The layer of maximum wind is the layer of the atmosphere in which the wind speed does not differ by more than 10% from the mean wind (or by about 20% from the maximum wind). From the wind profile, the following parameters of the LMW are extracted for the station:-

i) Mean wind speed

ii) Thickness

iii) Height (the arithmetic mean of the two heights bounding the LMW )

iv) Mean wind direction

An upper limit of the thickness of the LMW is fixed arbitrarily at 5 km and a lower limit of 60 kts is similarly set for the mean wind speed. If the sounding falls outside these limits, no LMW is taken into account for the stations. Such cases usually lie beyond the jet stream region. A typical wind profile and the LMW parameters derived from the profile are shown in Fig. 10.1.

10.3 In order to maximise the data over an area,some minimum information, such as the maximum wind speed and direction as derived from those soundings which fall outside the limits referred to above,are also utilised in the LMW analysis as additional material. In those cases where sounding is not complete, the vertical profile is extrapolated by taking into account time and space continuity and LMW parameters are evaluated from the extrapolated profiles.

10.4 In the analysis of the LMW charts the following features have been noticed over USA in the area where the PFJ is more frequent.

i) The LMW has the lowest elevation near the jet maximum. Upstream and downstream from the maximum, the elevation increases.

ii) The elevation and thickness of LMW are also a minimum just on the cyclonic side of the jet axis at a distance of about 100 miles.

iii) The gradients of the heights of LMW are stronger normal to the jet axis than along them.

## 11. Jet Stream as seen in Satellite Pictures

11.1 Satellite pictures show extensive cloud formations associated with jet stream, which are probably one of the longest cloud systems seen in satellite pictures. These cloud formations have a characteristic appearance and thus help to reveal the presence of a jet stream in the neighbourhood; some of them may also help to locate the position of the jet axis. Four types of jet-associated cloud organisations have been noticed in satellite pictures. They are:

i) long shadow lines
ii) sharp edged large ci-sheet
iii) longitudinal ci bands or streams
iv) transverse bands in ci formations

The long shadow lines and sharp-edged large ci-sheets are usually associated with PFJ. The jet axis could be placed parallel to the shadow line or the northern boundary of the ci sheet is either coincident with or slightly to the north of the jet axis. The northern boundary of the cloud sheet is sharp, long and usually anticyclonically curved. The jet cirrus is most often observed where the winds follow a broad anticyclonically turning path; where the jet stream turns cyclonically, the ci is rarely detectable.

11.2 Over India, longitudinal or transverse ci bands are the types generally met with rather than the shadow lines or the large ci shields. Corresponding land-based observations have shown that these jet stream clouds are mostly cirriform clouds with a fair amount of alto clouds (mainly Ac) mixed up. Although the STJ over India is a quasi-permanent feature of the daily charts over the country during the winter, still the ci bands do not form every day.

They appear only in association with large amplitude troughs, when certain amount of advection of moist air takes place at high levels over the country, resulting in the formation of clouds. The clouds form only ahead of the trough line.

11.3 In the case of longitudinal bands or streaks, they are oriented closely parallel to the wind flow or at small crossing angles. The jet stream axis is located just to the north of these streaks, nearly parallel to the streaks. In the case of the transverse bands, the transverse elements are nearly perpendicular to the flow at the jet level. The axis of the jet stream lies just to the north of cloud configuration.

11.4 Transverse band type cloud configurarion is associated with strong jet streams; turbulence is also more with a strong jet stream and it is believed that as a consequence, these transverse clouds develop. It has been found that larger vertical wind shear and smaller lapse rates are associated with the transverse bands while smaller vertical shear values and larger lapse rates are associated with longitudinal bands. A typical case of transverse band jet stream cloud is given in Fig. 11.1.

## 12. Mean and Daily Location of the STJ over India

12.1 The mean location of the axis of the STJ is roughly along 27°N over northern India during the winter months. Since the STJ is a stable feature of the general circulation as mentioned in Sec.3, even the monthly mean position such as the one given in Fig. 3.1 should indicate the latitudes where the STJ may be expected on most days of the month. However, it is the experience of the Indian Meteorologists that the axis of the STJ oscillates to some extent about the mean position. Sometimes, a second jet core may also be found in more southerly latitudes. When the upper westerly regime covers the whole of the country, even three cores have been reported on some rare occasions.

12.2 In order to study the variations in the daily positions of the jet core over the country, a statistics of the locations of jet core across long. 75°E was prepared from the analysis of the daily charts during the winter months of 1970–73. Only three months when the data position was satisfactory were studied. The analysis brought out the following points:

i) In all the three months, the axis of the jet across 75°E over the country lay between 26°N and 30°N on 70% to 75% of the occasions; even within this range lat. 27°N accounted for nearly 30% of the occasions.

ii) The jet stream over India comes to the south of 25°N only in January and February, the occasions of the jet coming to the south of 20°N being slightly more in February than in January. Shift south of 18°N is very rare.

iii) When the axis is not between 26°N and 30°N, it is located mostly (a) to the north of 30°N in December, (b) to the south of 26°N in January and February.

iv) It is noticed that with deep troughs in westerlies and active western disturbances across the country, the jet stream tends to shift to the south of its mean position, whereas, when a pronounced ridge dominates over the country, the jet axis tends to shift to the north of the mean seasonal position.

12.3 An analysis of the maximum winds reported by rawin stations in India during winter months of 1968–72 showed the following features:–

i) In the latitudes where the jet core is most commonly located (viz. between 26°N and 30°N) the maximum winds occur near 11.5 km on the highest number of occasions. On nearly half to two thirds the number of occasions, the jet core is between 10 km and 12.5 km. When the jet core shifts much south of the usual latitudinal position, its height appears to rise and is usually seen between 11.5 km and 13.5 km. In general, it has been found that on a large majority of occasions (50–75%), the level of the maximum wind is between 11 km and 13 km over the country.

ii) The speeds at the jet core are usually stronger in January and February than in December.

iii) The core speeds are also generally stronger when the core is in the near normal position (26°–30°N) than to the south of it.

iv) The highest core speeds recorded have been of the order of 200 kts.

12.4 Over the Indian Peninsula, sub-tropical ridge (in the upper troposphere) reaches the lowest latitudes towards the end of winter (February–March). On daily charts the ridge line fluctuates about the mean position. In extreme cases it may not be present at all and the westerlies may extend upto the equator to which a reference has been made already in the introductory part of this article. When the upper westerlies extend far to the south, the STJ also tends to shift to a more southerly position. To study the extension of frequency of occasions the westerlies to low latitudes, an analysis of the 200 mb winds at Gan and Trivandrum was made. In this analysis, winds less than 10 kts were omitted as they may represent only light variable wind conditions associated with the sub-tropical ridge line. It was seen ~~from the table~~ that westerly components are most frequent in January. Hence in January, the chances of westerlies coming to very low latitudes is high, compared to the other two months (December and February). Another feature was that westerly winds of jet strength (60 kts or more) were hardly ever noticed at Trivandrum at this level.

## 13. Jet Stream and Weather

13.1 Over northern India where the STJ is seen, the usual low level circulation feature is an anticyclone and generally the weather is dry. However, the dry weather is interrupted by the passage of western disturbances and their induced lows.

13.2 The western disturbances are characterised by their associated trough systems in the lower and mid-troposphere (sometimes extending into the upper troposphere). When these systems move across the country, we may notice the following features in the westerly flow:-

i) There is a general strengthening of the westerly flow over the country. Stronger westerlies may extend over a deeper layer of the atmosphere than during a quiescent weather period. The westerlies may also extend further south over more southerly latitudes than in the normal.

ii) The westerly maximum over north India may strengthen and often reach values of the order of 130-150 kts.

Associated with the high speed centres along a jet axis, we have upper divergence in the left exit and right entrance sectors, caused by the advection of positive vorticity. When such wind maxima are superposed on the low level low pressure systems (over north or central India) the resulting weather may be well-marked. Thunderstorms may also occur over such areas.

13.3 When induced lows form over Gujarat State, Madhya Pradesh etc. and cause weather over the central parts of the country, it is found that the upper westerly field strengthens over the central parts of the country and north Peninsula. The maximum winds over these areas may be more than the usual strength. On such occasions the STJ itself may shift southwards to these areas - particularly when there is also a deep upper westerly trough. On some other occasions a second jet axis may pass through this latitudinal belt, while the main jet core may remain in its mean seasonal position. Examples of these are discussed in Secs. 30-37.

## 14. Troughs in Westerlies - Introduction

14.1 In the middle and upper tropospheric westerlies, moving systems are relatively simple. The most common system is the wave perturbation. The dimensions of these perturbations are quite large, larger than those of the low level systems. We will deal first with the general properties of these wave disturbances and then proceed to some of the special characteristics of the waves that affect India during the winter period.

14.2 The waves in the upper westerlies may be divided into two broad classes – (i) long waves (which are also called 'Rossby Waves' or 'Planetary Waves') and (ii) short waves. 'Short Waves' are also known as 'Cyclone Waves' because of their intimate association with surface cyclones in the middle latitudes. On any typical day, we may see four to five major waves (long waves) around the hemisphere. They are one of the large scale features of the general circulation. Superposed on these long waves are the short waves, which move through the long waves. Typically, a middle latitude long wave has a wave-length around 6000 to 8000 km, while a short wave has a length of 2000 to 3000 km.

## 15. Long Waves

15.1 Long waves usually have a wave-length in the range of 50° to 120° of longitude – (corresponding to wave numbers 6 to 3). Atmosphere shows a strong preference for long wave numbers of 4 to 5 around the hemisphere. The actual number of long waves seldom differs by more than one from the stationary wave number.* Long waves are also of large amplitude and are noticeable though a deep layer in the mid- and upper troposphere (usually between 700 mb and 200 mb levels). Their amplitude increases upward. Long waves are either stationary or slow moving. The long waves are conservative and hence they change only slowly with time. On nearly two-thirds of the time, the wave number is conserved. They do not appear or disappear suddenly on the charts; it usually takes a few days for any major change in the long wave pattern. Hence, it is absolutely necessary to maintain strict continuity from day-to-day in respect of the long waves in the analysis of the extended area upper air charts.

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* For definition of "Stationary wave number" see page 3 of FMU Rep.No.V-2.

## 16. Identification of Long and Short Waves

16.1 The most convenient level for identifying the long waves is the 300 mb, where the patterns are smooth. Over India and the neighbouring areas also, this level is suitable since the mean height of the Himalayas is well below this level and the flow is not likely to be greatly distorted by the mountains.

16.2 It is sometimes easier to identify ridges (or wedges) of the long wave than the troughs. Inspection of the charts for a single synoptic hour may not be sufficient to identify the long waves. A sequence of a few charts is necessary. Since long waves are slow moving, the speed being of the order of 1 to 2 degrees of longitude (at 40°N) for 24 hours, while the short waves move with considerable speed, mean charts for periods of 3 to 5 days will eliminate the fast moving short waves, and the long waves alone will stand out. As an aid in the identification of the long waves, it is useful to prepare some continuity charts also such as

i) zonal profiles of mean height of 500 mb surface between certain latitudes or

ii) Hovmoller diagram*

16.3 In contrast to long waves, short waves are numerous; their amplitude is small and decreases upward. What we see on any upper air chart is a combination of short and long waves caused by the super-position of the short waves on the long waves. This leads to apparent intensification or weakening of the wave systems noticed, when we examine a sequence of daily charts. When a short wave ridge and a long wave ridge are in phase, the ridge becomes accentuated. Similarly short wave troughs intensify as they approach a long wave trough and weaken as they move toward the long wave ridge.

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* Hovmoller diagram has the geographic longitude as the abscissa, and time as the ordinate. The values of the mean height of the 500 or 300 mb surface over a latitude belt 15° to 20° wide, are entered at the corresponding geographic longitudes and subsequently contour lines are drawn. From the analysis, short-waves and long waves can be identified (see Hovmoller, 1949).

16.4 Over oceanic and other large stretches of data-void areas, it is difficult to locate the individual short waves and to follow them from day-to-day. Perhaps it is mostly the long waves that we see on the analysed charts over the oceanic areas.

16.5 When we prepare 24 hours height changes at 500 mb level, the centres of 24 hrs. fall and rise areas identify the short wave trough and ridge positions. The centre of 24 hrs. falls representative of the short wave tends to trace out the long wave pattern as short waves are steered by long waves. Short waves are also steered by "blocks" and large closed highs and lows aloft.

16.6 On an average, there is some proportionality between the amplitude and the wave length, such that longer waves tend to have larger amplitude. Thus both the latitudinal as well as the longitudinal extent of the long wave is more than that of a short wave. Observations show that the wave-length is a most independent of height from about 700 mb to 200 mb.

## 17. Thermal Structure

17.1 The thermal structure of the long waves is characterised by warm wedges and cold troughs. In the case of short waves it is the reverse - viz. the troughs are warm and ridges are cold. Thus while in the case of long waves, the contour (or streamline) and isotherm pattern are nearly in phase, they are largely out of phase in the case of short waves. This feature should be kept in view while doing the isotherm or thickness analysis.

## 18. Movement of Trough

18.1 We have already referred to the slow movement of the long waves and the fast movement of the short waves. Long waves move at a rate of about 1 to 2 degrees of Longitude (at Lat. 40°N) per day (speeds upto 15 kts have been quoted). Short waves travel almost with the speed of wind at 700 mb. level.*

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* Some authors put it as the speed of wind at the level of non-divergence.

Long waves may even move slowly against the zonal current (i.e. retrograde).

The speed of the wave is given by the equation.

$$c = u - \frac{\beta L^2}{4\pi^2}$$

where c is the speed of propagation of the wave

u – the zonal wind speed

L – the wave length

and $\beta$ – the variation of the Coriolis parameter with latitude.

From the equation it will be seen that for a given wave-length and latitude, the waves move faster if the zonal wind speed is greater. Also for a given wind speed, the speed is greater for short than for long wave-lengths.

18.2 The speeds of movement of the wave (particularly long waves) are related to the wave patterns in the contour and isothermal fields on an isobaric surface. This relationship is found to hold good fairly well in practice, in a qualitative sense. The relationship may be stated as follows:-

i) Progressive waves:

When the amplitude of the streamline (contour) is less than the amplitude of the isotherms, the wave pattern progresses in the direction of the zonal current. The wave is then said to be "progressive".

ii) Stationary waves:

When the isotherm pattern coincides with the contour (or streamline) patterns, the wave becomes stationary. Such waves are called "stationary waves".

iii) Retrogressive waves:

The wave will move from east ~~and~~ to west against the zonal current, when the amplitude of the isotherm is smaller than the amplitude of the contour pattern. These waves are called "retrogressive waves".

18.3 In a permanent wave, the isotherms have the same shape at all the levels, as a rough approximation. Since westerlies increase with height in the mid- and upper troposphere and the speed of the wave is independent of the height,we get the following relationship.

i) Progressive waves:

The amplitude of the contour pattern increases with height and tends to approach the amplitude of the isotherms at the height where the zonal wind reaches a maximum.

ii) Stationary waves:

The contour pattern coincides with the isotherm pattern at all levels. Their amplitude are independent of height.

iii) Retrogressive waves:

The amplitude of the contours will decrease with height and the contours will become nearly coincident with the isotherms at the height where the zonal wind reaches a maximum.

18.4 Short waves are always progressive waves. They travel fairly fast, at an average rate of about 10 to 12 degrees of latitude for 24 hours. The speed may be in the range of 20 to 40 kts. Retrogression is noticed only in the case of long waves. Observations show that real retrogression is a rare occurrence. However, the phenomenon known as 'discontinuous retrogression' is common. By this the following sequence of events is meant. An existing long wave trough weakens while a minor trough further upstream develops and gradually becomes the prominent one. This is merely an apparent retrogression. Retrogression is seldom localised. It usually affects several waves and the entire wave pattern around the hemisphere readjusts itself in about a week's time. A decrease in zonal wind or a southward shift of the zone of maximum wind, usually precedes the onset of retrogression.

## 19. Formation of New Waves

19.1 So long as waves are progressive, no new troughs develop. New troughs are usually found to form when the actual wave-length significantly exceeds the stationary wave-length, when according to Rossby's equation, the wave becomes retrogressive. Under such conditions either of the two following occurs:

i) A new major wave may form thus increasing the wave number.

ii) A discontinuous retrogression may occur as discussed in the previous paragraph.

Such changes in wave pattern are always associated with formation of intense low pressure systems at sea level. When the wave number increases in this manner, the wave-length correspondingly diminishes and the waves once again become progressive.

## 20. Divergence and Vorticity associated with Sinusoidal Waves

### 20.1 Divergence

20.1.1 The mean divergence ($\bar{D}_A$) at any level ahead of a sinusoidal wave is given by Palmen and Newton* as

$$\bar{D}_A \approx \frac{16\pi^2 A}{\bar{f} L^3} \times V\,(V - V_L)$$

where $\bar{D}_A$ is the mean horizontal divergence over an area

$A$ is amplitude of the wave

$\bar{f}$ Coriolis parameter at the central lat. of the wave

$L$ Wave length

$V$ Wind speed

$V_L$ Wind speed at the level of non-divergence.

The wind field (i.e. $V$ and $V_L$) is essentially the same for long and short waves. Besides there is some proportionality between the amplitude and the wave length (in well-developed waves $A = \frac{1}{4} L$); with these conditions, the above expression for divergence ($\bar{D}_A$) shows that for waves of similar shapes, (i.e. with the same ratio between amplitude and wave length), the upper tropos-

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*Eqn. 6.9 of 'Atmospheric circulation systems'- by E. Palmen and C.W. Newton.

pheric divergence is inversely proportional to the square of the wave length. The mean divergence in short waveis, therefore, about an order of magnitude larger than the mean divergence in a long wave. Numerically the divergence with a short wave is of the order of $10^{-5}$ $sec^{-1}$, while with a long planetary wave it is only of the order of $10^{-6}$ $sec^{-1}$.

20.1.2 The magnitude of the divergence will be large,

i) if the wave length is small, or

ii) if the wind speed is large and significantly different from that at the level of non-divergence. Since the divergence is dependent upon the term $(V-V_L)$ which is representative of the vertical shear, the baroclinicity of the basic current is also involved in the divergence. Troughs associated with jet streams, where large vertical shears are involved, have large divergence. The convergence and divergence in a sinusoidal wave, due to curvature is given in Fig. 20.1.

## 20.2 Vorticity and Vorticity Advection

20.2.1 The importance of the upper tropospheric waves to the synoptic meteorologist lies in the divergence (convergence) associated with them, resulting in vertical motion and the production of weather. In the previous paragraph we have discussed the divergence associated with a trough in terms of some of the parameters defining the geometry of the trough. Since divergence and vorticity are related, we can also discuss the regions favourable for development of weather in terms of vorticity advection. Vorticity advection is positive when wind blows from high to low values of vorticity. (By convention cyclonic vorticity is taken as positive and anticyclonic vorticity as negative). Advection of vorticity $(A_Q)$ is given by the term*

$$A_Q = -V^2 \left[\frac{\partial K_s}{\partial s} + K_s K_n\right]$$

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* Eqn. 16.6.2 of "Weather Analysis and Forecasting - Vol.I" by S. Petterssen.

where $V$ is the wind speed,

$K_s$ is the curvature of the streamline and

$K_n$ is the orthogonal curvature

Since vorticity advection is proportional to the square of the wind speed, it is very large in the jet stream regions.

20.2.2 A schematic representation of the vorticity and its advection in typical wave patterns is shown in Fig. 20.2. In Fig. 20.2(a) we have a sinusoidal wave and in Fig. 20.2(b) and (c), a sinusoidal wave pattern with confluence and diffluence respectively superposed. In Fig. 20.2(a), streamlines/contours are sinusoidal and parallel. $\frac{\partial K_s}{\partial s}$ is negative downwind and positive upwind from the trough, with numerical maxima at the inflexion points. In such streamlines, $K_n$ is very small everywhere. In this type of configuration, vorticity advection is rarely large, since vorticity varies evenly from trough to ridge. In Fig. 22 (b) and (c) are shown patterns where confluence and diffluence are superposed on a sinusoidal wave pattern. In these patterns, there is a tendency for vorticity advection to be concentrated in the vicinity of troughs and ridges.

20.2.3 The above are idealised patterns; troughs encountered on actual charts differ appreciably from the idealised patterns. In actual cases, it is found that appreciable amounts of vorticity advection are limited to small areas, separated by vast areas of insignificant amounts.

20.2.4 It would be ideal if numerical values of the magnitudes of vorticity and its advection are available to the operational forecasters. In the absence of such numerical data, location of zones of large vorticity advection from a visual inspection of the geometry of the trough pattern is all that can be attempted. But a visual inspection can only give an idea of broad areas of vorticity advection and cannot uniquely locate the "small areas" where vorticity advection is concentrated.

## 21. Thickness Patterns associated with a Trough or Ridge

21.1 The regions favourable for development in relation to the geometry of the wave pattern (as given by Petterssen) have been discussed in the previous paragraph. The problem has also been treated from the point of view of the mean thickness patterns from 1000–500 mb level, by Sutcliffe and a technique has been developed to assess development from the thickness patterns. Some typical thickness patterns and their characteristic features as given by Sutcliffe and Forsdyke are shown in Fig. 21.1.

21.2 Generally the thermal as well as the contour (or wind) field has a wave shaped pattern. At any level, thermal and contour patterns are not normally in phase. When the thermal wave is behind the pressure wave, the temperature field will help to intensify the pressure field by advecting positive thermal vorticity into the pressure trough and negative thermal vorticity into the ridge. The intensification stops only when the pressure field comes completely in phase with the temperature field. This effect is more pronounced for short waves than for long waves.

## 22. Interaction between waves at different latitudes

22.1 Since the westerlies extend over a very large latitudinal belt and the amplitude of the troughs in the westerlies are of the order of only 20° of latitude or so, it is possible to have a series of waves in the westerlies in the lower latitudes and another series of waves in the westerlies further north. These two series of waves are usually of different wave lengths and move with different speeds so that interaction between them is possible. When both are in phase, we may get a trough pattern extending over a very long stretch of latitudinal belt; when they are out of phase, the ridge in lower latitudes may be in juxtaposition with the trough in the more northerly latitudes and may lead to a region of confluence.

## 23. Cut off 'Lows' and 'Highs'

23.1 The deformation of the middle and upper tropospheric flow connected with the deepening waves in the westerlies often results in the formation of closed lows equatorward and closed highs poleward of the mainbelt of westerlies. These 'lows' and 'highs thus formed persist for quite some time. Such 'lows' form in the extreme southern portion of cold trough in the low latitudes and 'highs' in the northern portion of the warm ridges in the high latitudes and get separated from the trough or ridge. Hence they are called "cut off" lows and highs. Such situations are also called 'Blocking situations". On such occasions, the westerly flow is split into two streams around the high or low. The formation of the cut off 'lows' and 'highs' is related to the tilt of the trough and ridge line and this will be discussed in Sec. 26.

23.2 It has been noticed that upper cold lows form only in some preferred geographical regions. Over Afghanistan and adjoining north Pakistan and northwest India formation of cut off 'lows' is common. In cut off lows, cloudiness and precipitation are on the eastern side and clear skies occur in the west.

## 24. Zonal Index

The behaviour of the waves is dependant on the prevailing zonal index of the flow. With low index, there is pronounced meridional flow and the troughs are of large wave length and their motion is slow. With high index, zonal winds are strong and short waves move rapidly. Consequently cyclones also move rapidly all around the hemisphere. In the case of low index, with long waves preponderant, certain regions are dominated by cyclonic activity while extensive areas remain cyclone free.

## 25. Tilt of the Waves in the Vertical

25.1 The waves (whether short wave or long wave) extend through an appreciable depth of the atmosphere. The axis of the wave trough or ridge is usually displaced (in position) with height and this displacement is closely governed by the thermal structure of the atmosphere in which the wave is embedded. The patterns of the wave as analysed at different levels should, therefore, be consistent with the thermal (either thermal or thermal wind) patterns in the intermediate layers. The basic rules that govern the thermal and wind patterns are:-

i) Thermal winds (or shear winds) bear similar relation to thickness patterns as does geostrophic wind to isobaric patterns. The upper level pattern is obtained by the addition of the appropriate thermal wind to the lower level patterns.

ii) In barotropic regions, the flow pattern does not vary with height

iii) Wind maintains constant direction but increases in speed with height, where pressure and thermal patterns are similar.

25.2 Even a casual examination of the charts shows that trough or wedge lines tilt in position with height; the wave or ridge pattern also changes with height in intensity and to some extent in shape as well. These changes being due to the distribution of the temperature in the intermediate levels, can be explained in terms of the thermal winds and thermal vorticity. The main features of the vertical variations can be summarised as follows:-

i) Troughs are displaced towards cold air with height at a rate directly proportional to the temperature gradient and inversely proportional to the intensity of the trough. Similarly in the case of a ridge, the displacement is towards the warm air. Here the intensity of the trough or ridge may be defined by the vector change of wind horizontally across the trough or ridge. In view of this tilt with height, we may often find a sea level high vertically below a 500 mb trough (for example see Fig. 25.1.).

ii) Cold troughs and warm ridges intensify with height; similarly warm troughs and cold ridges weaken with height.

iii)The vorticity at the upper level is the sum of the vorticity at the lower level and thermal vorticity between the levels. Hence, if the total effect of the shear and curvature of thermal flow in the intervening levels is positive, there is greater cyclonic vorticity in the upper level flow than in the lower level. This vertical increase in cyclonic vorticity may be noticed either as an increase in the cyclonic shear or cyclonic curvature or both. Similarly if the total effect of shear and curvature of the thermal flow is negative, there is vertical increase anticyclonically in shear or curvature or both and the upper level pattern has less cyclonic vorticity than the lower level pattern.

25.3 In the case of westerly troughs, they usually tilt westwards with height. The long wave troughs generally amplify with height as they are cold troughs. On the other hand, the short wave troughs may dampen with height and disappear above a certain level, since they are usually warm troughs.

## 26. Tilt of the axis of trough and ridge in the horizontal

26.1 The axis of the trough in westerlies is in general not always oriented north to south. The axis makes an angle with the meridian (i.e. north-south direction); this angle from the meridian to a trough (or a wedge) line is called the 'tilt' and by convention positive tilt is counted from north to the west. It has been found that

i) There is a distinct tendency for troughs to intensify or weaken according to whether the tilt is negative or positive; similarly wedges tend to intensify or weaken according to whether the tilt is positive or negative.

ii) The amount of intensification or weakening is proportional to the amount of tilt.

26.2 During the life history of a wave in the westerlies, it is often observed that a trough rotates from a negative to a positive tilt. While the tilt is negative, the trough develops and sometimes may produce a 'cut-off' low also. When the trough rotates and the tilt changes to positive values, the wedges begins to build up and in pronounced cases a 'cut-off' or 'blocking' high may form.

## 27. Interaction with Waves in Easterlies

27.1 When a wave in westerlies in the northern latitudes and a wave in easterlies in the southern latitudes are in the same longitudinal belt, they may interact with each other, particularly if the sub-tropical anticyclone in that longitudinal belt is weak. The interaction may be in the form of a slowing down of the waves or their becoming stationary. Such an interaction results in the intensification of both the troughs and may even lead to the formation of tropical storms in the field of the easterly flow.

27.2 Sometimes the westerly trough may develop a large amplitude and extend southwards temporarily to the latitudes normally occupied by the upper easterlies. When the easterlies reform, the extreme southern portion of the westerly trough may get cut off from the main trough further north and form as a trough in the easterlies.

27.3 In some regions – such as over Indian area south of lat. 15°N during winter – the flow pattern may be easterlies in the lower troposphere overlain by westerlies above. When a deep trough moves in upper westerlies under such conditions, a trough may be induced in the lower easterlies. But contrary to the usual westward movement of the trough in easterlies, the trough in the lower easterlies formed in this way may move eastwards along with the upper trough. Such a situation is sometimes noticed in the Peninsula. Further north also in northern and central India in association with active induced lows, the lower tropospheric pattern may show a wave like trough pattern in the easterlies which may move eastwards.

## 28. Locating Upper Level Flow Patterns Utilising Satellite Cloud Pictures

28.1 The large scale cloud configurations in the regime of the upper westerlies, seen in the satellite cloud pictures, are closely related to the upper level flow patterns, since the sinking and rising motions associated with the upper flow determine the regions of large scale cloud formations. The satellite observed cloud formations should, therefore, indicate the approximate locations of short wave troughs, ridges, cutoff lows etc. This subject is dealt with in detail in Sec.III-4 of WMO Tech. Note No. 124 ("The use of satellite pictures in weather analysis and forecasting"). A brief summary of the same is given below. The upper flow patterns are more easily identifiable from the infra-red imagery.

i) Large scale zonal flow occurs in regions of more or less continuous cloud band of width of 200-400 km, stretching over distances of several thousands of kilometres. The band is usually straight. The position of the frontal zone coincides with the cloud band. Breaks and irregularities in the band are due to superposed short waves.

ii) Large amplitude flow is characterised by a complex cloud system consisting of quasi-sinusoidal cloud bands of high or medium level clouds, with vortex cloud patterns corresponding to migratory short wave disturbances, poleward of the major band.

iii) A cut-off low appears as a cloud vortex separated from the main frontal cloud band.

iv) A cut-off high is associated with a long cloud band oriented from north or south, with anticyclonic curvature at its northern extremity.

v) The upper troughs can be located by vortices, comma-shaped clouds, areas of convective cloudiness and breaks in frontal bands. A well-developed cloud vortex indicates a circulation at the middle tropospheric levels, embedded in the trough. Enhanced cumulus convection and comma-shaped cloud formations are associated with local vorticity maximum and correspond to secondary troughs in a broad cyclonic flow. The location where the trough line intersects the frontal band can be determined from the appearance of the frontal cloudiness. Ahead of the trough there is ascending motion and the frontal band is solid and broad and to the rear of the trough line the frontal band breaks up due to the descending motion. The area where the cloudiness thus changes appearance in a marked manner will correspond to the position of the upper trough line. This transformation in frontal clouding is particularly well recognised in Infra-red pictures.

vi) The upper ridge line is the location where the large scale cloudiness due to the upstream trough begins to dissipate. The abruptness with which the clouds end at the ridge line is determined by the sharpness of the ridge (i.e.) the degrees of the anticyclonic curvature along the ridge.

28.2 An example of a relatively sharp eastern edge of cloudiness corresponding to the location of an upper ridge is given in Fig. 16.3 of FMU Rep. No. III-1.1. A few typical satellite pictures of cloudiness associated with upper troughs over northwest India, Pakistan, Afghanistan, Iran and adjoining areas are given by Bhaskara Rao and Moray (1971 IJMG). Additional examples may be found in the subsequent sections of this report where some typical case histories are considered.

## 29. Certain special features noticed over India and neighbourhood

29.1 Till now we have discussed the main properties of the troughs in westerlies in a general way. It is necessary to supplement it by information regarding their actual behaviour when the troughs approach and move across India as seen on the daily charts. For this purpose, the daily working charts at Poona as well as the northern hemisphere charts published by USSR for the past few years were gone through. The troughs in the latitudinal belt 25°N-45°N were studied at 500 mb and 300 mb levels and their chief properties as observed on these charts are summarised below. This material may serve as useful background information in the daily analysis and prognosis of upper air charts.

### 29.2 ~~Local~~ Location and Movement

i) A great majority of the troughs in westerlies reaching India could be traced backwards to central or west Mediterranean. A few could be traced even further west to East Atlantic. During the course of its travel from the Mediterranean to India, the system may be seen either as a trough or a closed low or as a closed low with a trough extending from it. The trough may undergo changes in intensity, orientation etc. as ~~they~~ it travels eastwards. Over the Mediterranean and the adjoining parts of southern Europe, the trough/low usually originates at the extreme southern end of a large amplitude wave trough over central Europe.

ii) Of those troughs that reach India, a fairly good fraction (nearly half) weakens off or gets damped while moving across Western Himalayas. Also, those that affect northeast India are much smaller in number compared to those that reach northwest India.

iii) The orientation, movement etc. of the troughs are influenced by the slow moving long wave patterns, blocking highs etc. The troughs in the latitudinal belt of north India, may also interact with another system of troughs in more northern latitudes as discussed in para 22.1. When the short wave trough in the longitudinal belt 20° to 40°N is in phase with the wave pattern further north, there is an apparent amplification of the trough system and the reverse is the case with a ridge. With general zonal flow, the trough moves more uniformly and it also preserves its shape. When a blocking high is further to the north (i.e. north of 40°N), the trough (in the southern latitudes) appears to show a weakening; again it may become well-marked as it moves further eastwards away from the longitudes of the blocking high.

iv) The frequency distributions of the location of the troughs and their speeds in the latitudes 25°N to 45°N during their travel from southern Europe and west Mediterranean to East Tibet are given below.

## TABLE - 2

Frequency of location of westerly trough

| Total | LONG E | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 51–55 | 56–60 | 61–65 | 66–70 | 71–75 | 76–80 | 81–85 | 86–90 |
| 235 | 32 | 24 | 29 | 45 | 45 | 24 | 23 | 13 |

(Based on positions as seen in USSR chart 500 mb. Jan./Feb./Dec. 1967 to 69)

## TABLE - 3

Percentage frequency of daily speed of movement of Westerly trough (Degree of Long. per day)

| Positions (Long °E) | Speed per day (in ° long.) | | | | Total No. of cases |
|---|---|---|---|---|---|
| | <6° | 6–10° | 11–15° | >15° | |
| 51–55 | 22 | 33 | 33 | 12 | |
| | 7 | 11 | 11 | 3 | 32 |
| 56–60 | 30 | 30 | 30 | 10 | |
| | 7 | 7 | 7 | 2 | 23 |
| 61–65 | 45 | 38 | 10 | 7 | |
| | 13 | 11 | 3 | 2 | 29 |
| 66–70 | 57 | 21 | 12 | 10 | |
| | 22 | 8 | 5 | 4 | 39 |
| 71–75 | 50 | 21 | 21 | 8 | |
| | 19 | 8 | 8 | 3 | 38 |
| 76–80 | 47 | 27 | 20 | 6 | |
| | 7 | 4 | 3 | 1 | 15 |
| 81–85 | 50 | 15 | 15 | 20 | |
| | 7 | 2 | 2 | 3 | 14 |
| 86–90 | 80 | 20 | — | — | |
| | 4 | 1 | — | — | 5 |

(Based on positions as seen in USSR chart 500 mb. Jan/Feb/Dec. 1967–1969)
Note:(1)In each line, the lower figures indicate the No. of cases (2) The difference between Table 2and 3 in the total No. of troughs is due to the fact that some troughs have weakened off in between.

It will be seen from Table 2, that there is a pronounced maximum in the longitudinal belt 65°E to 75°E (i.e. over Russian Turkistan, Afghanistan, north Pakistan and the adjoining northwest India). This maximum may be due to the slowing down of the troughs over this area or/as well as formation of new troughs – both of which are corroborated by synoptic experience. The most common speed is between 5° to 15° of lat. per day to the west of 65°E, and less than 6° in the longitudes belt 65 to 75°E. East of 75°E, the speed is more variable.

v) When the trough is associated with a closed low to the north, the speeds of travel of the closed low and the trough may be different. Often, we notice the trough line moving faster than the closed low, so that different parts of the trough line have different speeds and there is a cyclonic turning of the orientation of the trough line, and this can lead to the weakening of the troughs and the embedded low as the 'tilt' of the trough becomes positive (ref. to Sec. 26).

vi) The frequency distribution in each $100^2$ sq. km. square of the positions of closed lows at 500 mb level during the winter (Dec., Jan. and Feb.) is given in Fig. 29.1. The centres of the lows have been taken from the Northern Hemisphere charts published by USSR and pertain to the winter period of 1967-69 (covering a total of 9 months). The figure shows that the lows are most frequent over southern Europe and the adjoining Mediterranean. They move eastwards across Black Sea, Caspian Sea and Aral Sea. At 65°E, the Western Himalayas and the TIEN SHAN Ranges effectively obstruct further eastward movement of the lows and bifurcate the track – one branch going northeastwards towards Lake Baikal while the other branch comes into the extreme northern parts of India.

The larger number of lows over Russian Turkistan, Afghanistan, north Pakistan and northwest India brings out the effect of the mountain ranges in slowing down the lows as well as in inducing formation of fresh lows over the area. Black sea area is another region of maximum frequency.

Fig. 29.1 may be compared Fig. 2.1 of FMU Rep. No.III-1.1 (in respect of the surface lows over the area) and the similarity between them may be noted.

### 29.3 Wave-length

The troughs usually have a wave-length varying from 30 to 45 degrees of longitude, on over 70% of the occasions. The most common (nearly a third of the occasions) wave-length is of the order of 35° to 40°. Troughs with wave-lengths less than 20° of longitude are small in number. Wave-lengths greater than 50° of longitude are also very few over the area.

### 29.4 Amplitude

The large majority of the troughs have an amplitude less than 20° of latitude. On over half the number of the occasions, the amplitude is between ten and twenty degrees; the amplitude may be as much as thirty degrees. Over south Asia (45°E to 110°E) large amplitude troughs are more common in the area between 60°E and 75°E. This is also the area where the troughs tend to slow down or where new troughs form, as discussed in para 29.2(iv). On occasions, the trough may get linked up with a wave trough further north and extend over a very large latitudinal belt.

### 29.5 Slope

The troughs in westerlies have a westward slope with height. The slope between 500 mb and 300 mb, is usually less than 5 degrees of longitude (i.e. the slope is roughly 1/150). Slopes exceeding 10° of longitude are very rare. There have been a few occasions, (about 5%) of an eastward slope with height (such a slope being noticed in the case of a few slow moving troughs).

## Discussion of Typical Synoptic Situations

### 30. Deep Trough in Westerlies over India and Pakistan - 23 December 1969

30.1 A trough in westerlies moved across the extreme northern parts of the country on 19th, and reached Sinkiang and Western Tibet on 20th; while remaining more or less stationery during the next 3 days, it developed large amplitude.

The charts for 23 December 1969 are given in this section to illustrate some features of the trough in westerlies.(Fig. 30.1).

30.2 On 23rd December, the deep trough had its axis (at 200 mb level) from Sinkiang to off Konkan coast. In association with the trough, the STJ had shifted well to the south of its normal position over Pakistan and Western India. A feature to be noted, is the general weakening of the winds near the trough line. Over Gujarat, northwest India and northwest Madhya Pradesh the speeds were less than even the minimum required for a jet (viz. 60 kt). Thus the STJ was apparently discontinuous over this area. Ahead of the trough, the wind speeds increased considerably downstream. Extended charts show that the speeds reached 200 kts over south Korea (near 35°N) (~~Fig. 30.2~~). The weaker winds near the trough line and their strengthening downstream towards the ridge are characteristic features.

30.3 Upstream from Western India, there was another trough over Black Sea, east Mediterranean and the UAR, with its axis along 30°E, so that in the latitudinal belt of 30°–35°N, the wave length was about 50° of longitude.

30.4 The presence of another jet stream in the north over southern USSR in the latitudinal belt 35°–40°N is another noteworthy feature. In the eastern portion of the chart, the two jets merged together to form a single intense jet over Korea and Japan.

30.5 The main features to be noticed in this case are:–

i) The trough was more marked in the upper troposphere (300–200 mb) than in the lower troposphere. The wavelength was about 50° of longitude. The trough was also not fast moving (at least between 20th and 25th). These features would lead to the classification of the trough as a "long wave trough".

ii) The wind speed distribution was characteristic, with weaker winds near the trough line and stronger winds in the ridge.

iii) The STJ and the other jet stream further north merged together over East Tibet and China, leading to pronounced strengthening of the jet core winds to 200 kts over South Korea and Japan.

iv) The trough amplified over India and the amplification was probably related to the negative tilt (northeast–southwest orientation) of the trough.

## 31. Movement of a Trough from Iran to Northwest India
## – 8 to 12 January 1971

31.1 In the first week of January 1971, a warm high* was present over Iran, Pakistan and Afghanistan and an east-west oriented trough was extending from the hills of west Uttar Pradesh to north Arabian Sea (Fig. 36.1). In this trough, a low developed over northeast Arabian Sea and Sind. In the meantime, a fresh trough in westerlies from the west was also approaching Iran. Under the influence of these two systems, (viz. the 'low' over northeast Arabian Sea and Sind and the approaching westerly trough), the high over Iran and Pakistan weakened.

31.2 On 8th January, 1971, during the course of the day, the fresh westerly trough moved into Iran, completely destroying the high previously over the area and the trough became the dominant feature on the chart. The trough was well-marked, extending southwards into north Arabian Sea. By 1200Z of the day, the trough moved into Pakistan and was extending from 40°N, 60°E to almost East Central Arabian Sea across Sind (through nearly 25 degrees of latitude) (Fig. 31.1).

31.3 During the next 24 hours the trough moved further eastwards and reached northwest India and the adjoining Pakistan by 9th evening. However, on 10th there was a retrograde movement of the trough, under the influence of a short wave trough in westerlies which came over the northern parts of Iran and on 10th evening, the trough was extending from Russian Turkistan to Gulf

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* The case of this warm high is discussed in Sec. 36.

of ~~Omen~~ Oman and northwest Arabian Sea and possibly further south into West Central Arabian Sea also (Fig. 31.2).

31.4 The trough became progressive once again reached northwest India and Gujarat State by 12Z of 11th (Fig. 31.3). During the subsequent 24 hrs., it weakened as it moved across India.

31.5 The above sequence has brought out the following features:-

i) As a westerly trough moved to Iran, the previously existing high there weakened and the trough also developed large amplitude extending into north Arabian Sea. Due to an approaching shortwave trough the main trough showed an apparent retrograde motion on 10th. The trough was rather slow-moving while over Iran and Pakistan and northwest India, which was also partly due to the retrograde motion. After reaching northwest India, the trough moved relatively quicker and also weakened. The development of large amplitude while over Iran-Pakistan, its slow movement over these areas and a relatively quicker movement and weakening over India are some common features (Ref. to para 29.2). The weakening of the trough while over India, appears to be due to the thermal trough overtaking the pressure trough (see thermal wind charts of 11th – 1200 GMT) (Fig. 31.4).

ii) The trough was mainly for the south of 40°N.

iii) Northern Hemisphere charts (500mb) show that almost simultaneously with the weakening of the westerly trough over India, the other well-marked quasi-stationary trough upstream over Central Mediterranean and north Africa also weakened and a nearly zonal westerly flow set in from east Atlantic to mid-Pacific to the south of 50°N. (Fig. 31.5 and 31.6).

iv) The STJ which had shifted southwards over western India, under the influence of the high over Iran and Pakistan, continued to remain in a southerly location on account of the well-marked trough over Iran, Pakistan and north Arabian Sea. On most days during the period, the axis of the jet was running from north Konkan northeastwards to central Uttar Pradesh and thence to eastern Tibet. The jet was also moderate to strong with core winds exceeding 100 kt. Two typical cross-sections normal to the flow over India, showing the position of the jet over western India are given in Fig. 31.7(a) and (b). There was a good down-gradient cross-contour orientation of the jet axis from north Konkan to East Tibet and West China, and the core wind strengthened from about 100 kts over Konkan to over 150 kts over East Tibet and West China (for instance see 11th 1200Z 200 mb chart).

v) Another interesting feature* is that the westerly flow did not extend much southwards in any pronounced fashion, although there was a deep trough over Pakistan and northwest India. The sub-tropical ridge was quite strong over southeast Asia and the Bay of Bengal, so that over south Peninsula, the upper tropospheric winds were strong southerlies and south-easterlies. These strong southerlies joined up with the southwesterlies over central parts of the country and north Arabian Sea to strength the STJ. In the near equatorial region also, the upper tropospheric winds were strong easterlies, speeds reaching upto 40 kts, which is rather unusual in this season.

## 32. Movement of a large amplitude trough across the country 16 to 22 January 1970

32.1 In this section$ we will illustrate the movement of a deep trough across India and Pakistan and its weakening as it moved across the country.

32.2 An upper air low travelling eastwards moved into West Iran on 16th and a well-marked trough formed there on 17th. The trough amplified further and moved eastwards and on 19th it extended from Pakistan to Central Arabian Sea (Fig. 32.1). Ahead of the trough, the upper tropospheric winds strengthened over India and became southwesterlies. The trough moved to northwest

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* Compare with the cases discussed in Sections 34 and 35.

India on 20th, when its amplitude became slightly less (Fig. 32.2). During the next 24 hrs, it moved rapidly eastwards and its amplitude became still less. By 22nd it moved away into West China and weakened.

32.3 Some of the main features of the trough were:

i) The trough was confined to the latitudes south of 40°N; it was not connected to any trough system further north.

ii) On the 19th, when its amplitude was the maximum, the trough extended as far south as 10°N.

iii) The amplification of the trough on 18th and 19th and the subsequent decrease in the amplitude were controlled by the thermal structure of the trough. This is illustrated by the sequence of charts giving the relative positions of the trough in the contour/wind field and in the thermal field. For want of adequate data in the west, the sequence is given only from 19th (Fig. 32.3). On the 19th when the contour trough was ahead of the thermal trough, there was an amplification of the contour trough. On 20th, the two troughs coincided; by 21st the thermal trough overtook the contour trough when the contour trough weakened. Thus the amplification and weakening of the trough were related to its thermal structure viz., the trough amplified when the thermal trough was to its rear and weakened when thermal trough lay ahead of the contour trough.

iv) The amplification of the troughs as they approach Pakistan and northwest India and their weakening as they move across the country is a common feature.

v) The amplitude of the thermal trough was generally greater than the amplitude of the contour trough, so that the trough was a progressive one.

vi) In association with the movement of the trough across the country, the STJ shifted southwards, and was well to the south of the mean seasonal position, particularly in the western India. The core of the jet was running from north Konkan to Assam on 20th. The two cross-sections over western India perpendicular to the flow shows that the core was passing over Bombay and Gwalior (Fig. 32.4 and 32.5). Over Bombay, the core was near 300 mb (which was much below the usual altitude for the STJ) while over Gwalior, the STJ was in its near normal altitude.

vii) The trough and the jet were also associated with development of well-marked cyclonic circulations in the lower troposphere and widespread precipitation over the northern and central India.

## 33. Accelerating Jet Stream from Northwest India to South Japan – 10 December 1970

33.1 Generally the westerly jet stream accelerates between northwest India and south Japan. While the wind speed at 200 mb in the mean is only about 90 kt over northwest India, it increases to about 150 kt over south Japan. This strengthening may be either due to the confluent flow between the STJ and the PFJ which is to the north of India or between the STJ and the flow around the strong southwest Pacific anticyclone. An example of the strengthening of the jet stream as it flows from India to south Japan is shown in Fig. 33.1. In this case, there was a confluence of the STJ with another jet stream to the north of India, the two currents meeting over Eastern Tibet and West China. A case of confluence between the STJ and the southerly/southwesterly flow around the subtropical anticyclone has been referred to in Sec. 31.

33.2 The three cross sections along 77°E (Western India) 90°E (northeast India and eastern Tibet) and 105°E ~~110°E~~ (West China), bring out the general strengthening of the westerlies downstream, as well as the strengthening of the core winds from about 100 ~~90~~ kt over northwest India to about 140 ~~120/130~~ kts over extreme northeast India and West China (Fig. 33.2 a,b,c). The cross-section along 77°E also brings out both the cores – viz. the core of the STJ over India and the other core to the north of India near 37°N. The temperature profiles at 500 mb and 300 mb levels along these longitudes clearly show the strengthening of the temperature gradient also downstream (Fig. 33.3). The temperature gradient at 300 mb over the region to the north of 23°N increased considerably along 90°E and 105°E compared to the gradient along 77°E. The gradients were also more at 300 mb than at 700 mb or 500 mb level.

## 34. Shift of Strong Westerlies to the south of the Mean Seasonal Position – 4 January 1970

34.1 The upper air situation for 1200Z of 4.1.70 is presented here to give an example of the shift of the STJ southwards from its mean seasonal position over India, i.e. near about the latitude of Delhi (Fig. 34.1).

34.2 A deep trough in westerlies moving across USSR developed a cut off low on 3rd between Aral sea and Lake Balkash, where it persisted on the next two days (Fig. 34.2). During this period, for a few days, the flow pattern over central Asia and the adjoining Europe became more of a cellular type, and the zonal westerlies were restricted to the extreme northern parts of Asia and also to the south of 40°N. In the westerly flow to the south of 40°N, a trough in westerlies moved across Pakistan, north India and Tibet between 3rd and 5th.

34.3 On this occasion, the westerlies to the south of 40°N extended as far south as 7°N in the upper troposphere and the sub-tropical ridgeline~~s~~ at these levels was near about 5°N over the Indian sea area, which was a few degrees of latitude to the south of the mean seasonal position.

34.4 The cross-section along 75°E for 12Z of 4th (given in Fig. 34.3) shows that the core of the STJ was near Lat. 22°N (between Nagpur and Ahmedabad) which is well to the south of the mean seasonal position (Long. 27°N). Strong westerlies of speed over 50 kt extended upto 16°N. The anticyclonic shear to the south of this latitude was higher than the Coriolis parameter for that latitude and was almost double the value.

34.5 An examination of the 500 mb temperature field shows that progressively colder air was being brought over north India; while the temperatures in north India fell, those over north Peninsula ~~was~~ were nearly steady, thus leading to a steepening of the temperature gradient over the central parts of the country in the latitudinal belt Jodhpur–Bombay and the strengthening of the upper tropospheric winds there.

34.6 This instance also brings out that one of the factors that favour the shift of the STJ southwards is the presence of a cut off 'low' or 'high' to the north of India which splits the zonal westerlies into two, one branch going to the north of the 'cut off' system and the other branch to the south. In each of the split westerly branch, there could be a core of maximum winds or a jet. When such a split occurs, the westerlies to the south may extend much more towards the equator than normally and the jet stream also is found in a more southerly position. Sometimes these westerlies extend almost upto the equator.

34.7 Except for some high or medium clouds over the north India, the shift of the STJ southwards and the passage of the westerly trough did not cause any weather on this occasion.

### 35. Westerly flow extending to southern latitudes and shift of STJ to south – 15 January 1970

35.1 This is another case where the strong westerlies extended southwards. Over India strong westerlies prevailed in the upper troposphere over the whole of northern and central India and the north Peninsula and winds of speed 50 kts were noticed in the upper troposphere even at lat. 15°N. The flow was westerly over the whole of the Indian Peninsula.

35.2 In the hemispherical charts, it was noticed that a deep trough in westerlies (extending north–south practically over the entire East European and Asian landmasses) moved across between 9th and 17th from 30°E to 115°E (Fig. 35.1, 35.2 and 35.3). It became less marked by 15th as it reached the eastern USSR (Fig. 35.4). The weakening of the trough over Eastern USSR appears to be associated with the trough developing positive tilt (ref Sec.26). The southern end of the trough which apparently got cut off from the main trough, moved across the northern parts of India between 15th and 16th. (Fig 35·4)

35.3 After the major trough weakened over eastern USSR, the upper air flow was tending to become zonal over the whole of Asia. On 15th and 16th, the zonal westerlies were strong over the extreme northern parts (north of lat. 55°N) and also to the south of Lat. 30°N. In between, the gradient was slack and the flow was comparatively weak; minor troughs moved in the weak flow over the central Asia.

35.4 Over India, winds of speed about 100 kts prevailed over the whole of northern and central India at 200 mb level. The jet stream was more spread out than normally. The cross-section along 75°E over India for 15th-1200 GMT is shown in Fig. 35.5. From this diagram, it is clear that the spread out layer of very strong winds apparently contained two cores – one in the latitudes of Jodhpur-Gwalior (26°N) in the near seasonal position and the other over Bombay-Nagpur area (20°N). The southerly core was more prominent. Just to the south of this core, the anticyclonic shear well exceeded the Coriolis parameter. (At 200 mb the shear between Bombay and Begumpet, a distance of 2° of latitude was 50 kt, while the Coriolis parameter in this latitudinal belt is only about 10 kt per degree of latitude). The anticyclonic shear was much greater than the cyclonic shear to the north of the jet core.

35.5 On the 15th morning, the satellite pictures showed a long band of high and medium clouds extending from central Arabian Sea to Southeast Madhya Pradesh (Fig. 35.6). This was apparently associated with the jet stream. The development of induced lows and the extension of weather over the central parts of the country during the winter is often associated with the location of the jet core at more southerly latitudes, as in the present case. (See clouds and weather over Uttar Pradesh and Bihar in Figs 35·6 and 35·7)

35.6 The passage of the westerly trough over north India and the shift of the jet core to the south were associated with development of cyclonic circulations in the lower levels and weather over the country (Fig. 35.7 and 35.8). An induced low developed over South Rajasthan, north Gujarat and northwest Madhya Pradesh on 13–14th, which while moving eastward caused a spell of rain/thunderstorms over Uttar Pradesh, Bihar, Madhya Pradesh and Vidharba on 16–17th. The occurrence of thunderstorm activity near the jet axis is noteworthy.

### 36. Well-marked High over Iran and Pakistan and the shift of the STJ southwards – 5 January 1971

36.1 The situation for 5 January 1971, is illustrative of a 'cut-off' high over Iran and Pakistan and the consequent shift of the STJ to southerly latitudes over north Arabian Sea and central India (Fig. 36.1).

36.2 In the rear of a well-marked trough in westerlies travelling across Pakistan and northwest India between 2nd and 5th January, 1971, a pronounced ridge moved in. A high was located in the northern end of the ridge and the high could be traced from north Arabian Peninsula, and the adjoining UAR on 1st, travelling slowly eastwards. Due to lack of data,it has not been possible to trace it ~~further~~ back and find out where and how the 'cut off' high formed. The high reached Iran and adjoining areas on 5th and at 1200 GMT was centred over central Iran when it was well marked extending throughout the entire troposphere from surface to almost 200 mb level. The winds over the southern parts of Pakistan and Iran, to the south of the high, were easterlies, in a region where normally the winds are strong westerlies. The 'high' was warm – cored.

36.3 With the high over southwest Asia, the STJ shifted well to the south of its normal position and passed across south Arabia, north Arabian Sea, Gujarat State and South Rajasthan. Further north over Western USSR, there was another jet stream (probably PFJ) to the north of the 'high'. These two jet streams became confluent over East China and south of Japan (Fig. 36.2).

36.4 The vertical section over western India on 5 January 1971 (1200Z normal to the flow pattern there is shown in Fig. 36.3. This clearly shows the core of the STJ over Ahmedabad. The cross-section also brings out the reversal in the temperature gradient between Jodhpur and Bombay occurring in the layer 200 mb —300 mb.

36.5 The APT pictures (ESSA 8 – orbits 9422 and 9421 ~~ITOS~~ – Fig 36.4 ~~orbit 434~~1) show the existence of the jet stream over north Arabian Sea, ~~and the~~ to north Bengal across Gujarat State by the transverse ci bands; the transverse structure ~~nature~~ indicating a strong jet was consistent with core winds of 110 kt observed over Ahmedabad (~~Fig. 36.4~~).

## 37. Shift of the STJ well to the North of the Mean Seasonal Position – 14 to 15 Feb.1971

37.1 Just as the STJ shifts to southern latitudes when a trough moves across Pakistan and India, the reverse takes place when a well-marked ridge happens to be over Pakistan and India. In this section we will discuss a case when the STJ shifted well to the north of its mean seasonal position.

37.2 In the rear of a trough which moved across western Himalayas and Tibet, a ridge came over Pakistan, Afghanistan and northwest India on 12.2.1971 (Fig. 37.1). The ridge was noticed between 700 mb and 300 mb levels. At 200 mb level the flow was nearly zonal south of 35°N. The ridge became well-marked during the next two days with a slight eastward movement and was noticeable above 300 mb also. The ridge joined up with another pre-existing ridge further north over central USSR and on 14th, the axis of the ridge system extended from north Arabian Sea to extreme north USSR between longitudes 60°E and 75°E at 500 mb (Fig. 37.2). This ridge, with two troughs on its either side, dominated the entire flow pattern over Asia on 14th and 15th. On the 15th the ridge line (at 500 mb) was over northwest India.

37.3 When the ridge came over India, the core of the STJ shifted to the north and on 14th and 15th the axis of the STJ was passing through Russian Turkistan and Sinkiang. The vertical cross-sections along 75°E for 12th and 15th February 1971 (shown in Fig. 37.3 and 37.4) clearly bring out the northward shift of the jet core from the near normal position (over Delhi) on 12th to 40°N on 15th. During the subsequent two days, the ridge pattern weakened and the flow became more zonal over India and the STJ also shifted once again southwards to its mean seasonal position.

37.4 Available data would suggest that the tilt of the ridge changed from positive to negative between 13th and 15th; and this was consistent with the strengthening and the subsequent weakening of the ridge.

37.5 On these days (14 and 15th) the sub-tropical ridge ~~on~~ line over the Indian area was well to the north of the normal position. Over the Indian Peninsula it was along 15°N, whereas the mean monthly position is along 8°N. With these changes, the flow pattern over the south Peninsula in the upper troposphere became easterly with winds reaching 40-50 kt over the extreme south Peninsula, Sri Lanka and in the near equatorial region.

37.6 During this period when the upper ridge predominated the flow pattern over India, there was very little clouding or weather over northwest India.

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110. Sutcliffe, R.C. 1951: The quasi-geostrophic advective wave in a baroclinical zonal current. QJRMS Vol.77, p.226.

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116. World Meteorological Organization, 1969: Aeronautical Meteorology. Technical Note No. 95, WMO No. 227, T.P. 121.

# DIAGRAMS

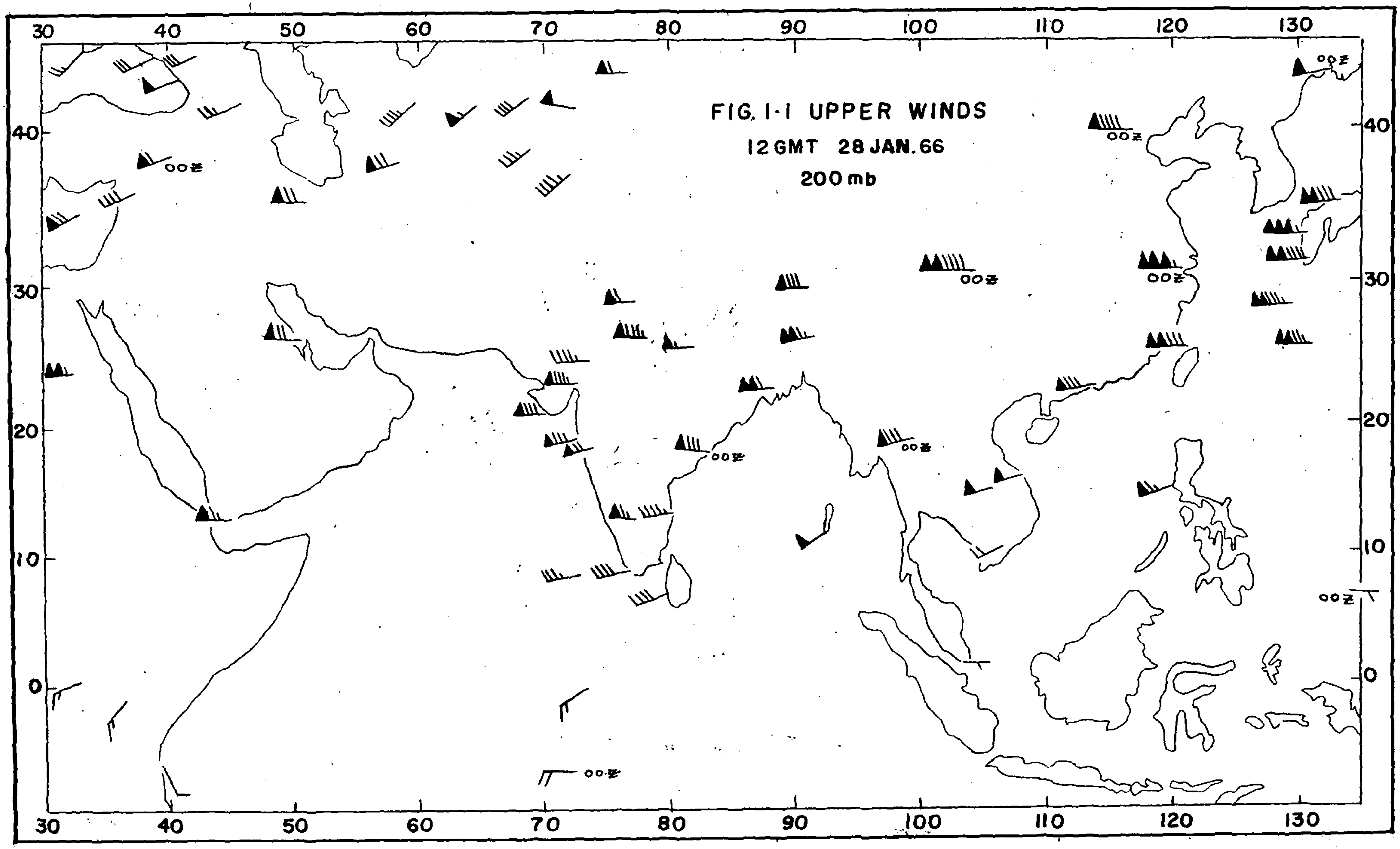
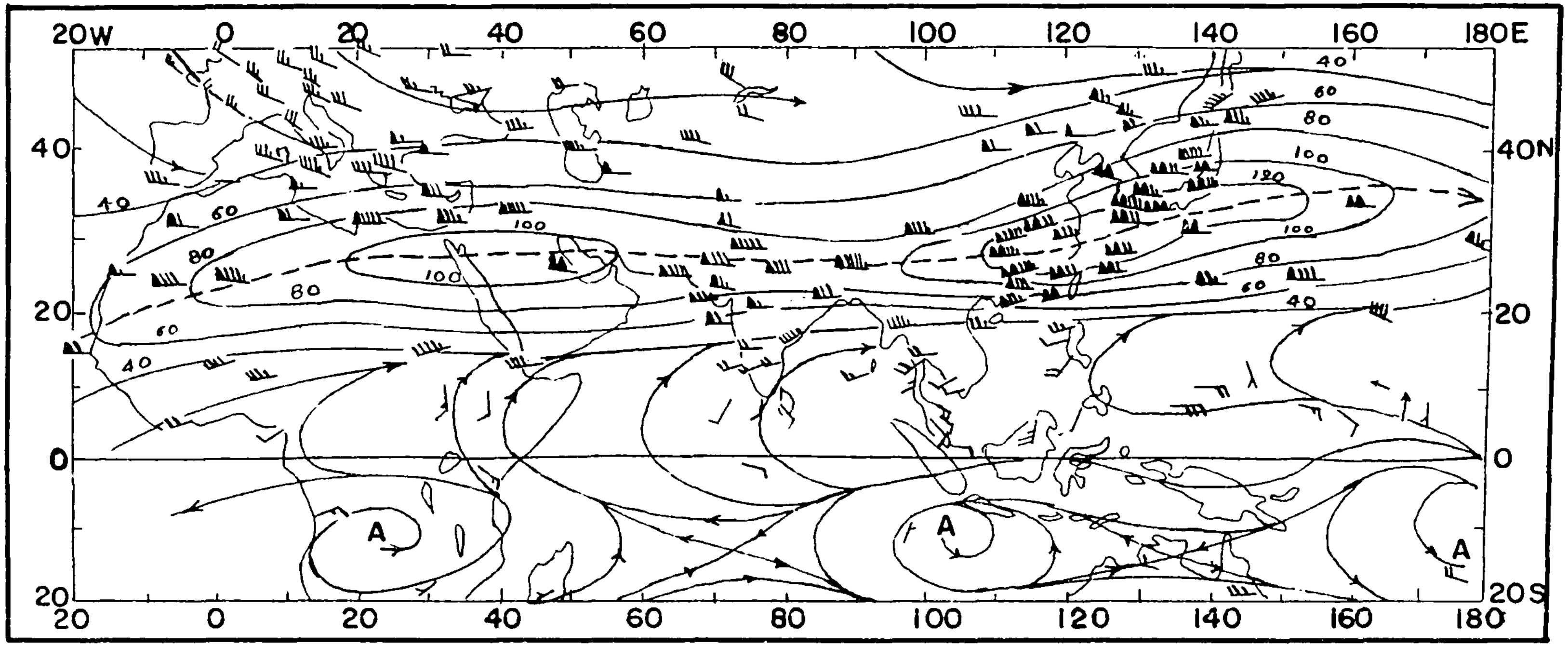


FIG. 1·1 UPPER WINDS
12 GMT 28 JAN. 66
200 mb

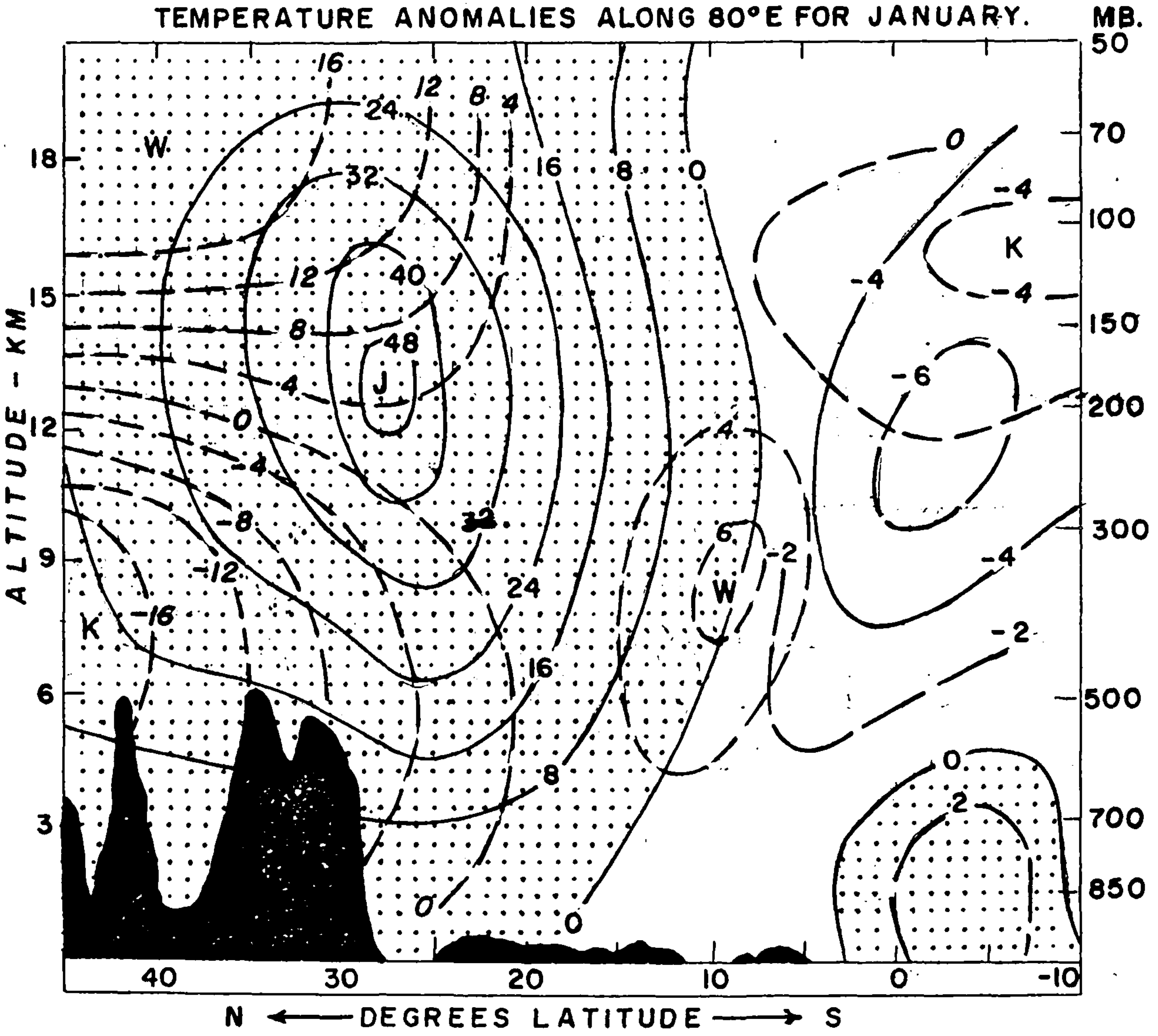
FIG. 3·1 MEAN SUB TROPICAL JET STREAM AT 200MB OVER AFRICA & ASIA IN JAN.



——·— Isotachs ——→ Stream lines ---- Jet core A - Anticyclone.

Reproduced from "Forecasting of upper winds & temperatures in tropical latitudes with special reference to Jet Streams" by P. Koteswaram. WMO Technical Note No. 95 (WMO-No. 227. TP. 121) pp. 218 - 228

FIG. 3·2 MEAN VERTICAL CROSS-SECTION OF ZONAL WINDS AND TEMPERATURE ANOMALIES ALONG 80°E FOR JANUARY.



Full lines = Zonal winds, mps.
Westerly positive
Easterly negative

Dashed lines = Temperature anomalies °C

Zone of Westerly winds : Dotted

Terrain : Stippled

(Reproduced from 'Forecasting Upper Winds and Temperatures in Tropical Latitudes, with special reference to Jet Streams" by P. Koteswaram, WMO Technical Note No.95 (WMO No. 227 TP.121) pp.218-228).

FIG. 4·1 Mean Vertical Profile for Delhi for Strong, Moderate & Weak Jets.

Reproduced from "A study of vertical wind profile of the Westerly Jet Stream over Delhi, using Radar Wind data" by R.Y. Mokashi, IJMG Vol.20, No.4, pp.361–368. (1969)

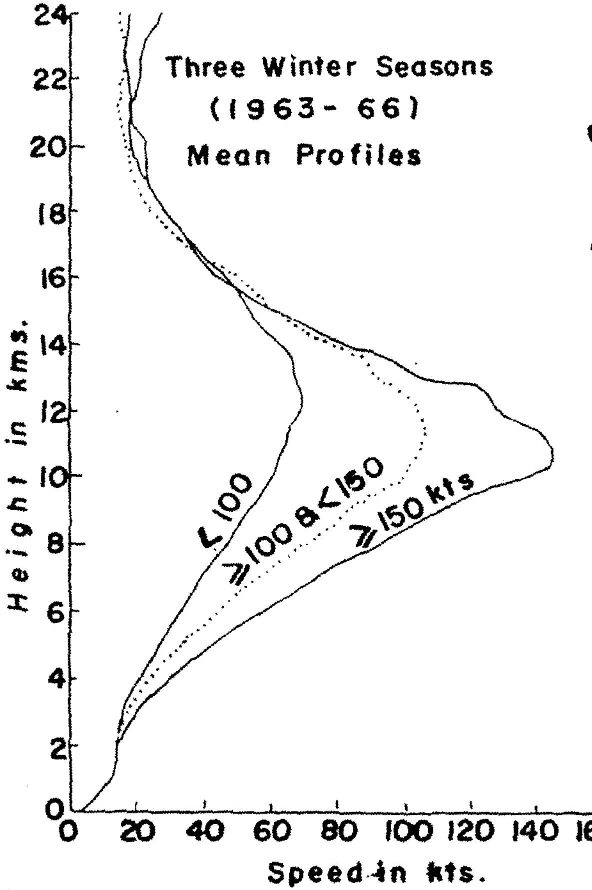


FIG. 4·2 Wind Profiles across India – Typical Cases

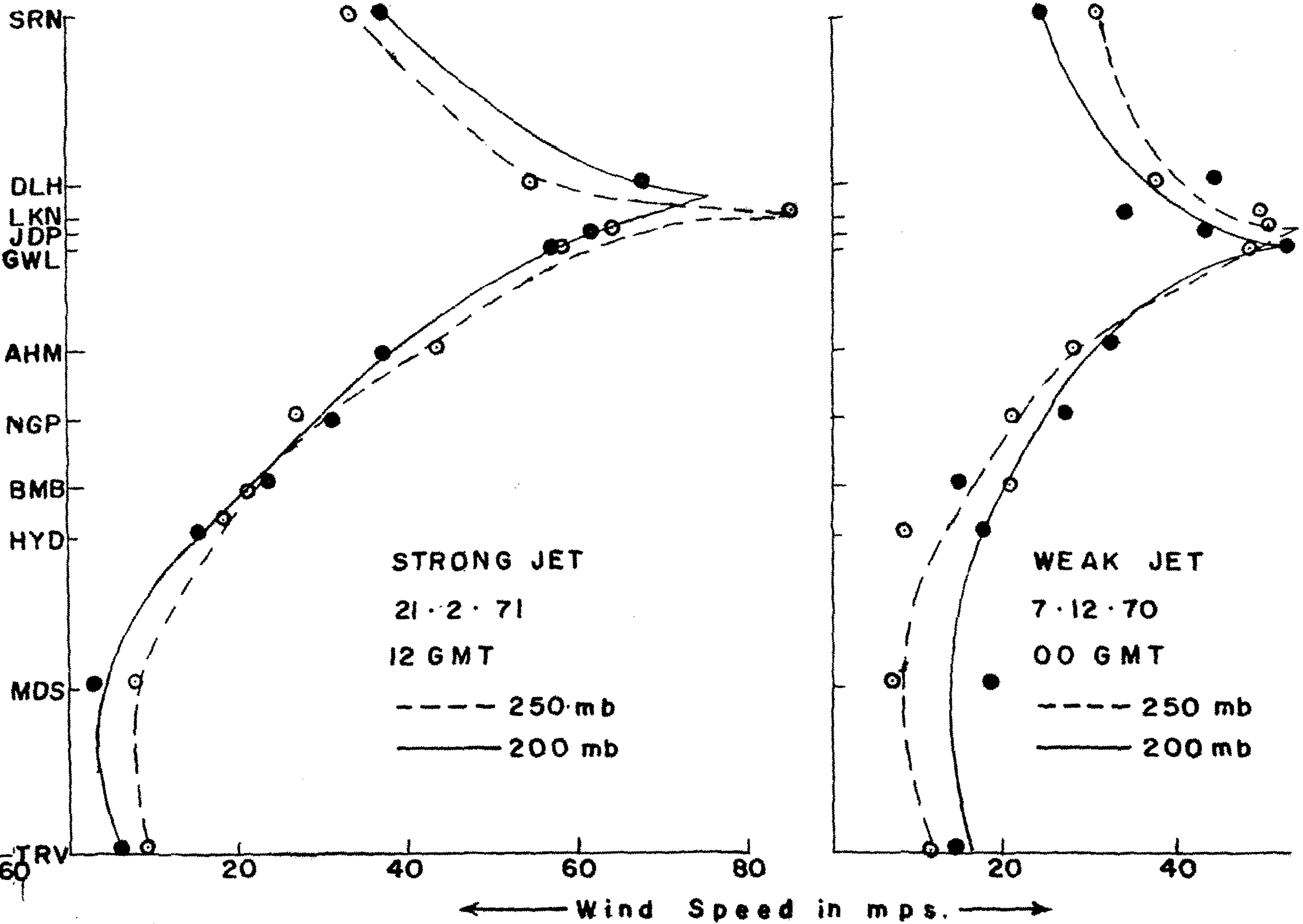
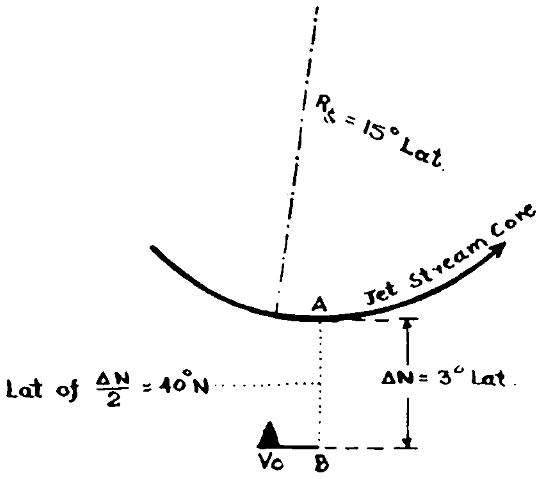


FIG. 4·3 (a)



Estimating the wind speed in the jet-stream core from an adjacent wind observation to the right of the core. The component $R_s$ is the radius of curvature of the stream line of the jet-stream core. The component $\Delta N$ is the distance of the observed wind $V_o$ from the unknown wind $V$, at the point A in the core. The increment $\Delta V$ which must be added to $V_o$ to estimate $V$ is composed of two components, $\Delta V_1$ and $\Delta V_2$. The component $\Delta V_1$, depending upon $\Delta N$ and the latitude at $\frac{1}{2}\Delta N$, is found in Fig.4.3(b). For straight streamlines $\Delta V_2$ is zero, and $V=V_0+\Delta V_1$. For curved streamlines, $\Delta V_2=(V\Delta N)/R_S$. The component $\Delta V_2$ is positive for cyclonic curvature, and negative for anticyclonic curvature. Since V is unknown, $V_o+\Delta V_1$ is used in its place to approximate $\Delta V_2$. For cyclonic curvature this first approximation is adequate. For anticyclonic curvature, a second approximation of $\Delta V_2$ may be necessary. Finally, $V=V_o+\Delta V_1 \pm \Delta V_2$. As an example, if $\Delta N$ is 3° lat. $\frac{1}{2}\Delta N$ is at 40°N lat, then, by Fig.4.3(b), $\Delta V_1$ is 54 knots. If $R_s$ is 15° lat, cyclonic curvature, $\Delta V_2$ is approximately $[(V_o+\Delta V_1)\Delta N]/R_s$, or (104x3)/15, or 21 knots. Then, $V=V_o+\Delta V_1+\Delta V_2$, or V = 50 +54 + 21, or 125 knots. Had the streamline curvature been anticyclonic, V would be approximately 50 + 54 – 21 knots, or 83 knots. By second approximation, $\Delta V_2$ is (83 x 3)/15 or 17 knots, and V is 87 knots.

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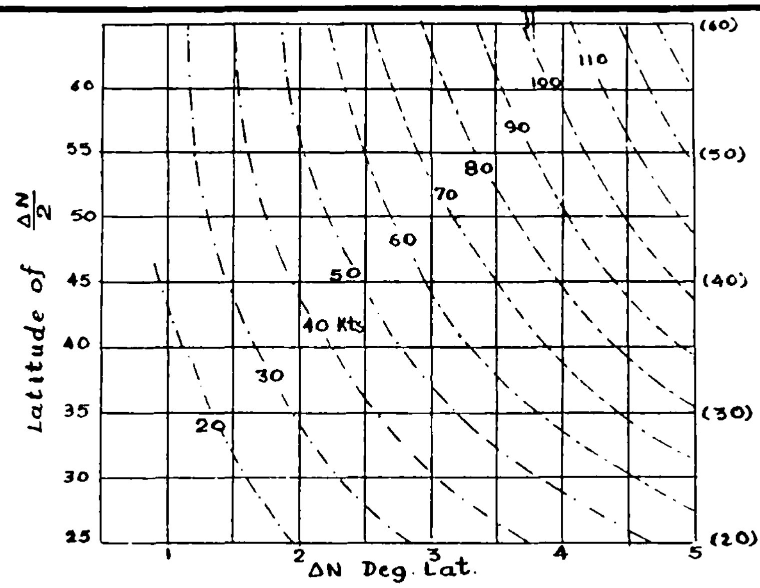
FIG. 4·3 (b)



Estimating the lateral shear of the wind $\Delta V_1$ between the unknown wind at the jet-stream core and an observed wind adjacent and to the right of the core, for straight streamlines. Assuming slightly positive absolute vorticity within 5° of lat. of the jet core, the shear values are given by the dot-dashed lines, and depend upon $\Delta N$, the distance of the observed wind from the jet stream and upon the latitude at $\frac{1}{2}\Delta N$. The parameters are illustrated in Fig.4.3(a) (Adjustment of the latitude lines has been made on the assumption, as suggested in "The Jet Stream" that the absolute vorticity is slightly positive. The lateral shear under conditions of zero absolute vorticity to the right of the jet stream is found by using for $\frac{1}{2}\Delta N$ the small latitude values in parentheses on the right side of this figure)

* Meteorol.Monographs, Am.Meteorol. Soc.2, No.7 (1954).

FIG. 4·4 GRAPHICAL METHOD FOR ESTIMATING THE POSITION & STRENGTH OF THE CORE OF MAXIMUM WINDS

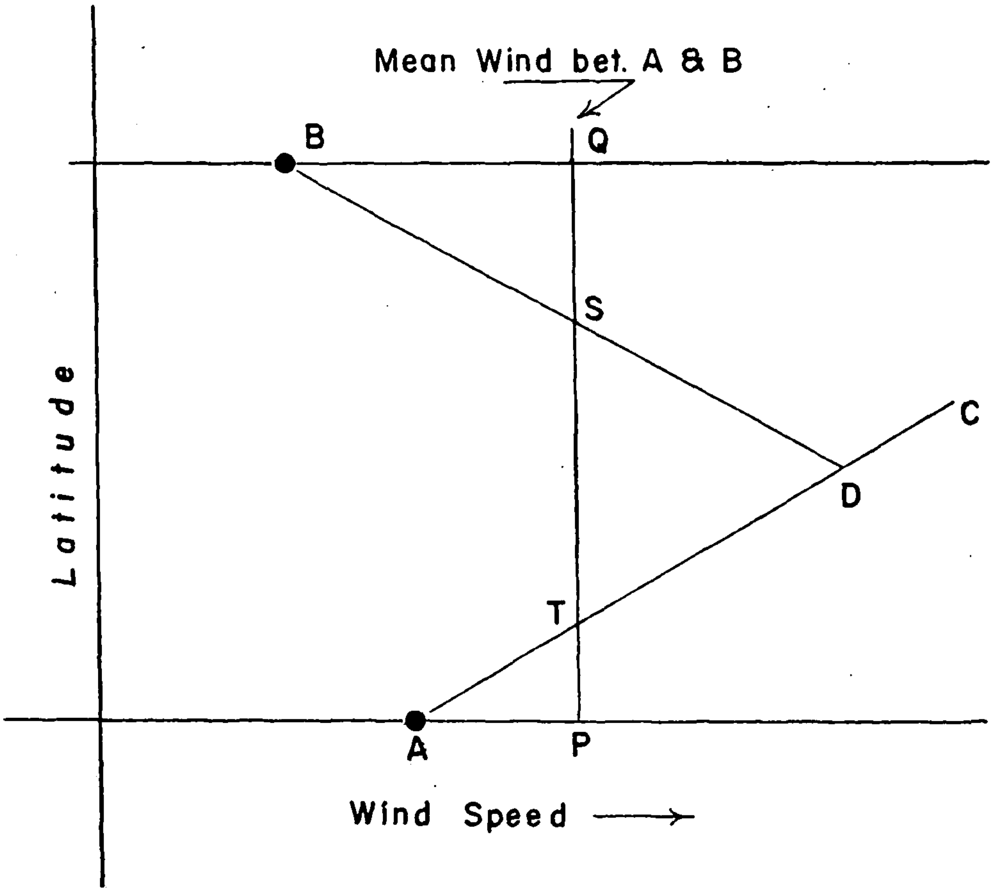


FIG. 5·1 UPPER WINDS 1200 GMT 20 JAN. 73

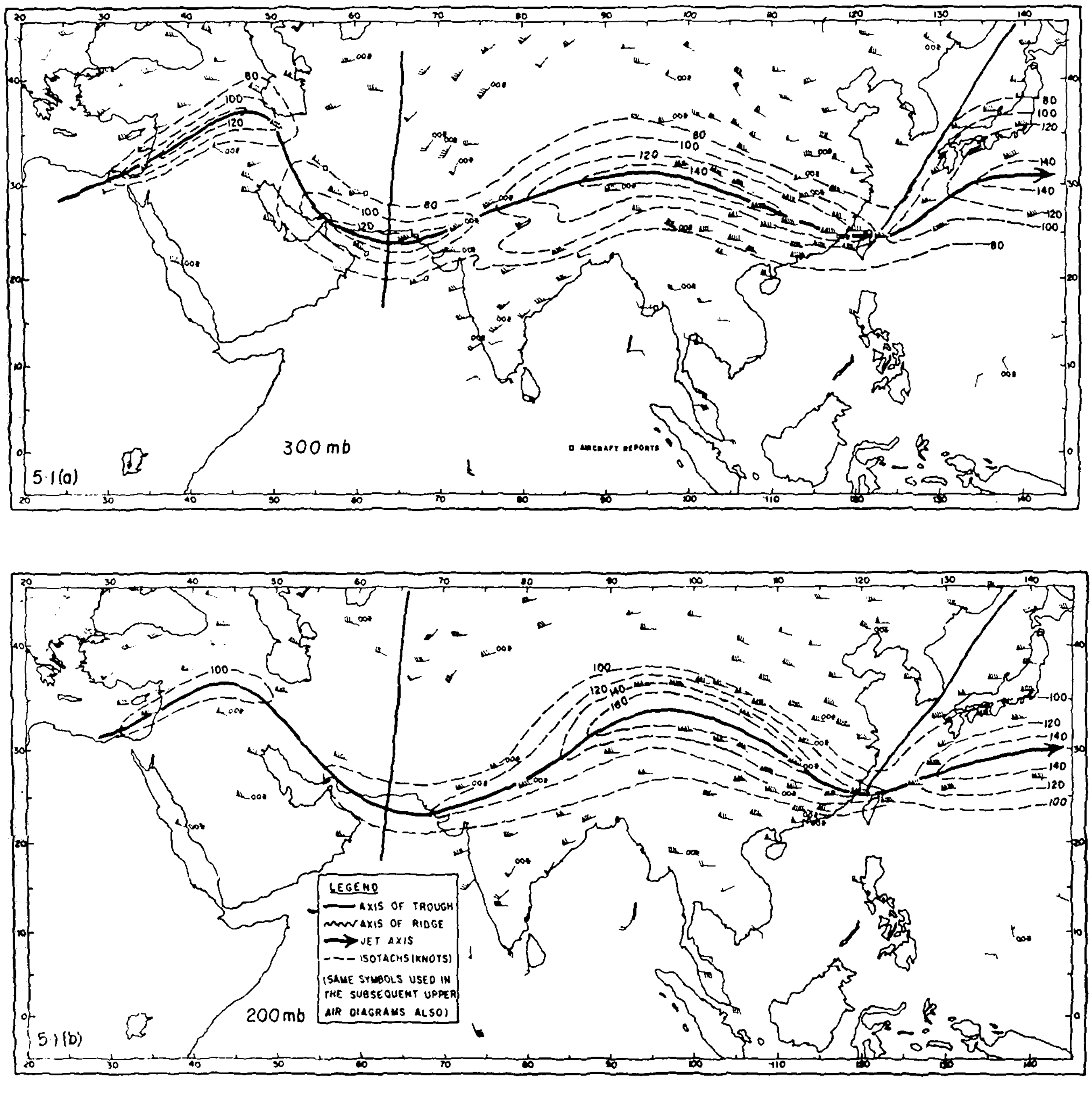


FIG. 5·2 TIME CROSS SECTION FOR NEW DELHI : 4-12 JAN. 70

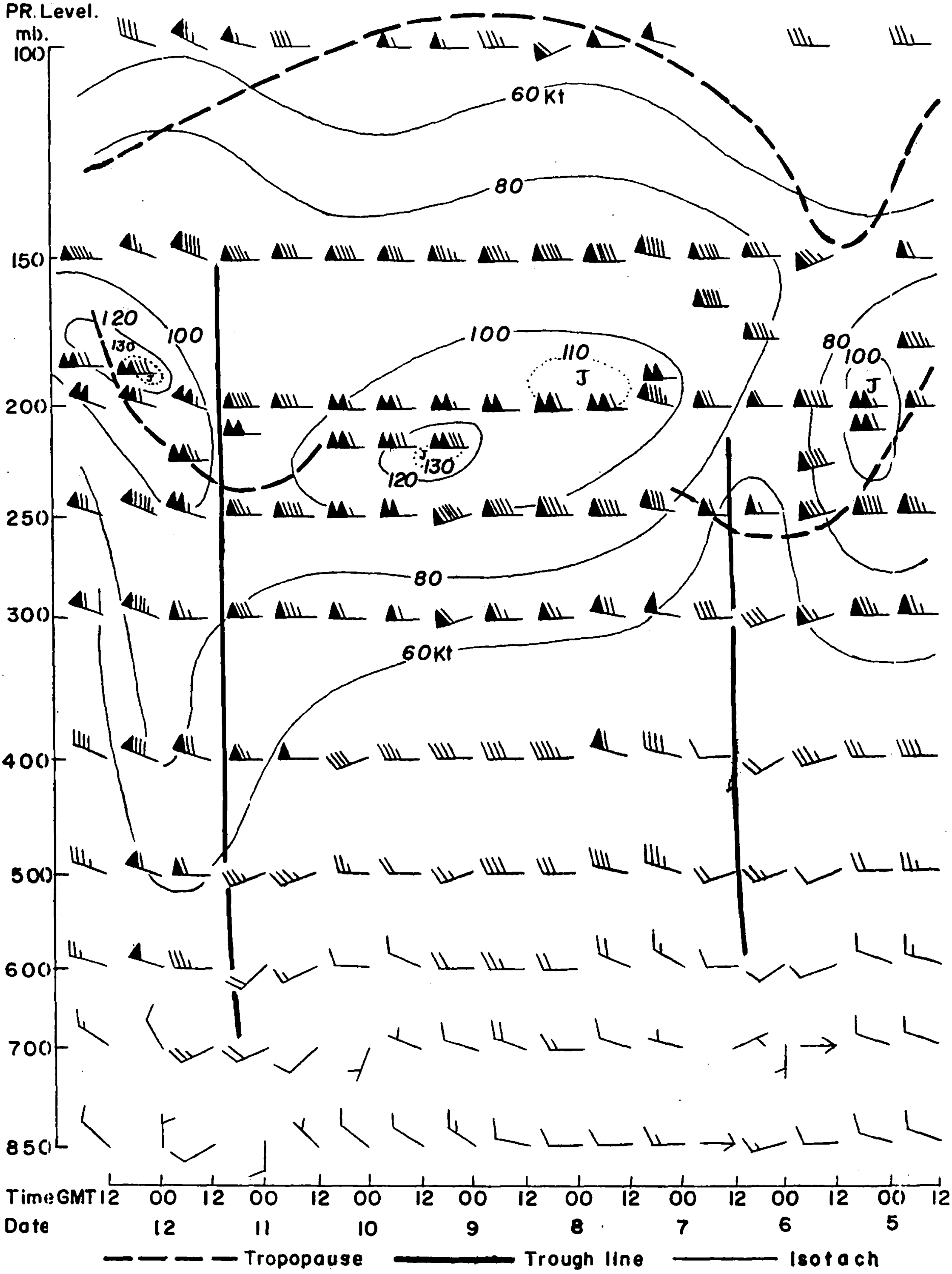


FIG. 5·3 SPACE CROSS SECTION ALONG 75°E FROM ALMA ATTA (43°N) TO GAN (1°S) : 12 GMT 10 FEB. 71

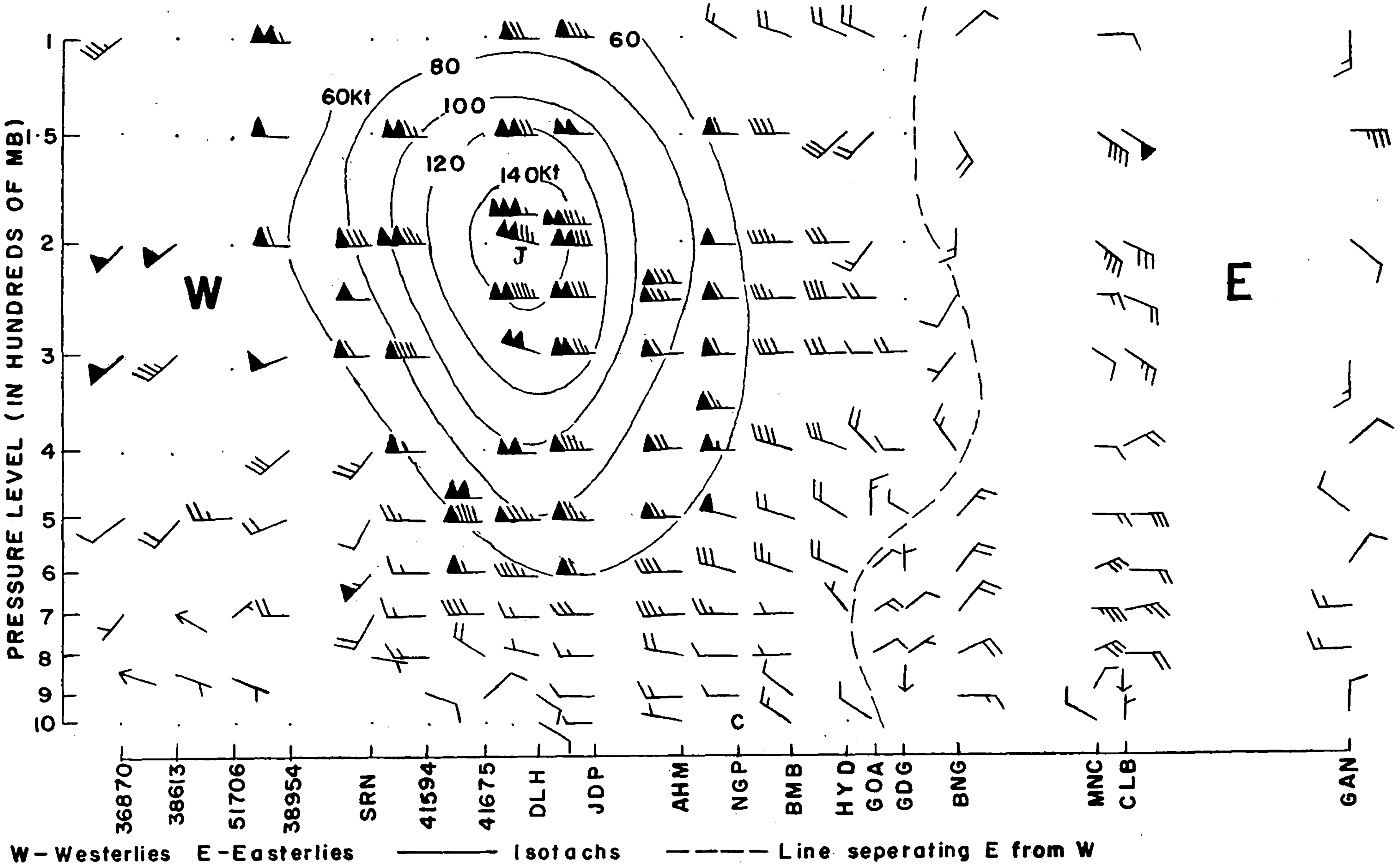
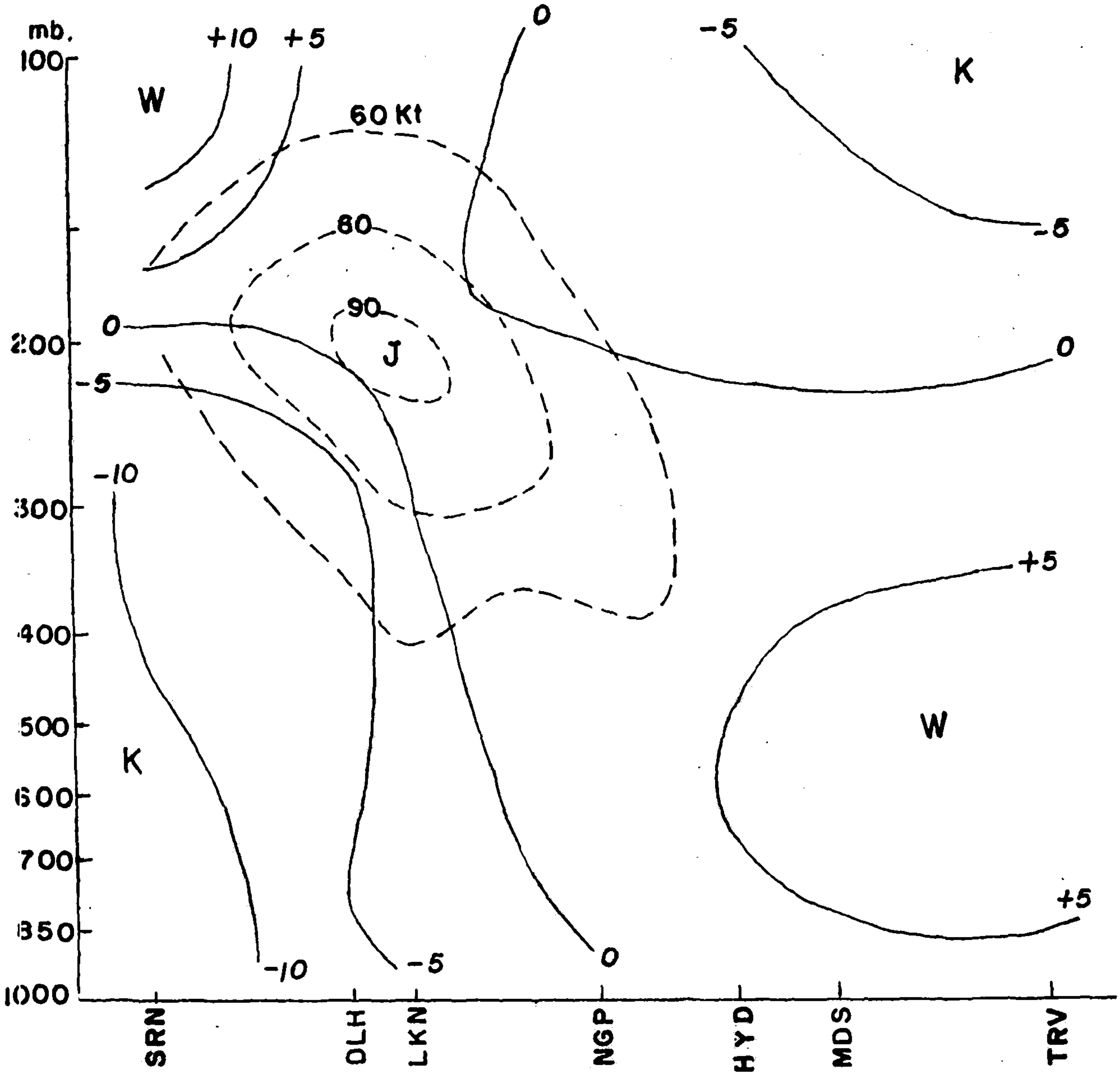


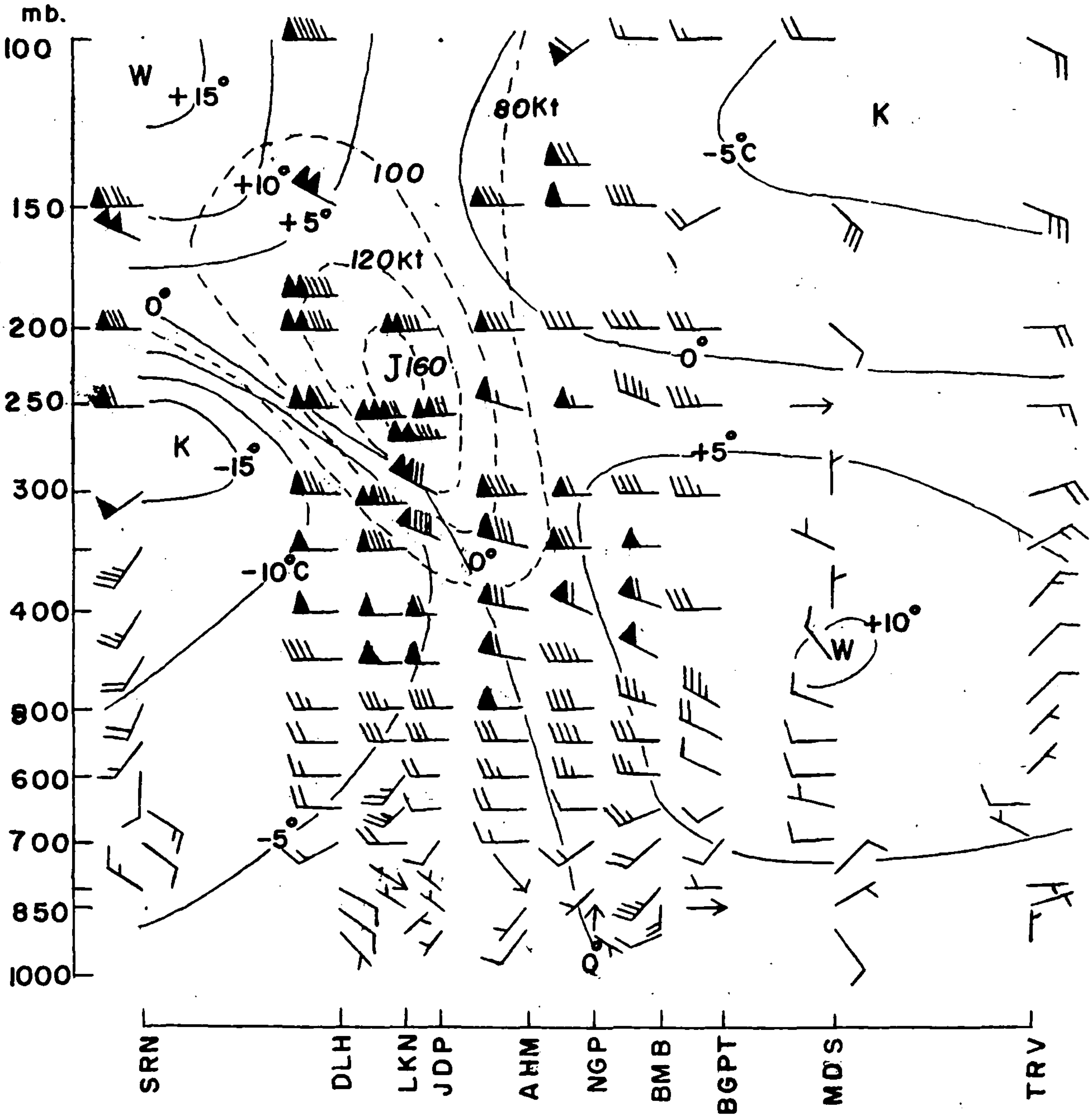
FIG. 5·4 MEAN TEMPERATURE ANOMALY CROSS SECTION ACROSS INDIA JANUARY 1968



Based on Fig. 1(a) and 1(c) of "Thermal and other characteristics of Sub-Tropical Jet Stream over India" – P.K. Misra (Symposium on Aeronautical Meteorology with special reference to SST. New Delhi, March 1970)

**W - Warm K - Cold**

FIG. 5·5 TEMPERATURE ANOMALY CHART : 12 GMT 21 FEB. 71



W - Warm K - Cold

FIG. 5·6 A PAIR OF TYPICAL TEPHIGRAMS ON EITHER SIDE OF THE JET AXIS

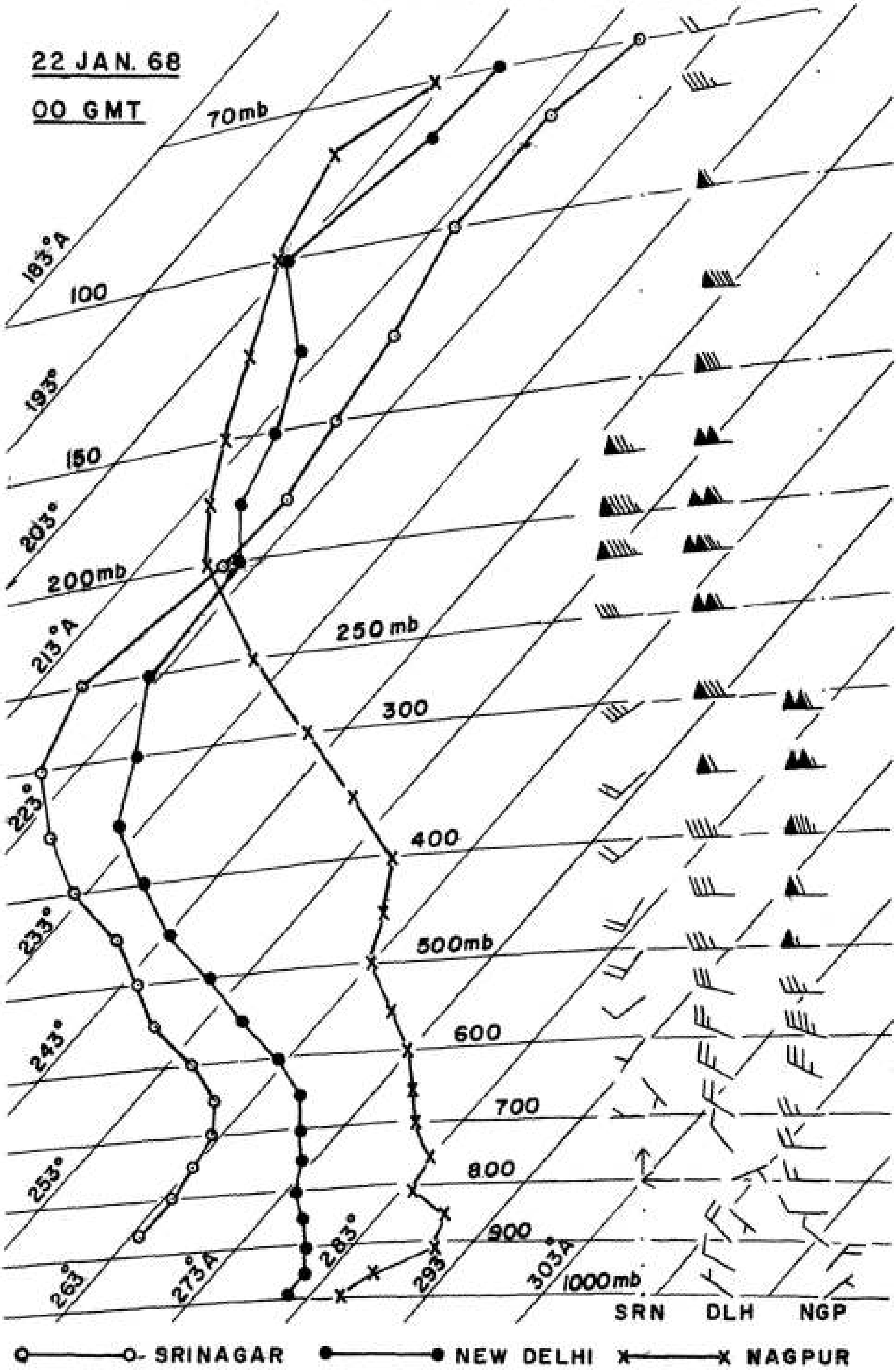


FIG. 6·1  UPPER WINDS 0000 GMT 28 JAN. 73

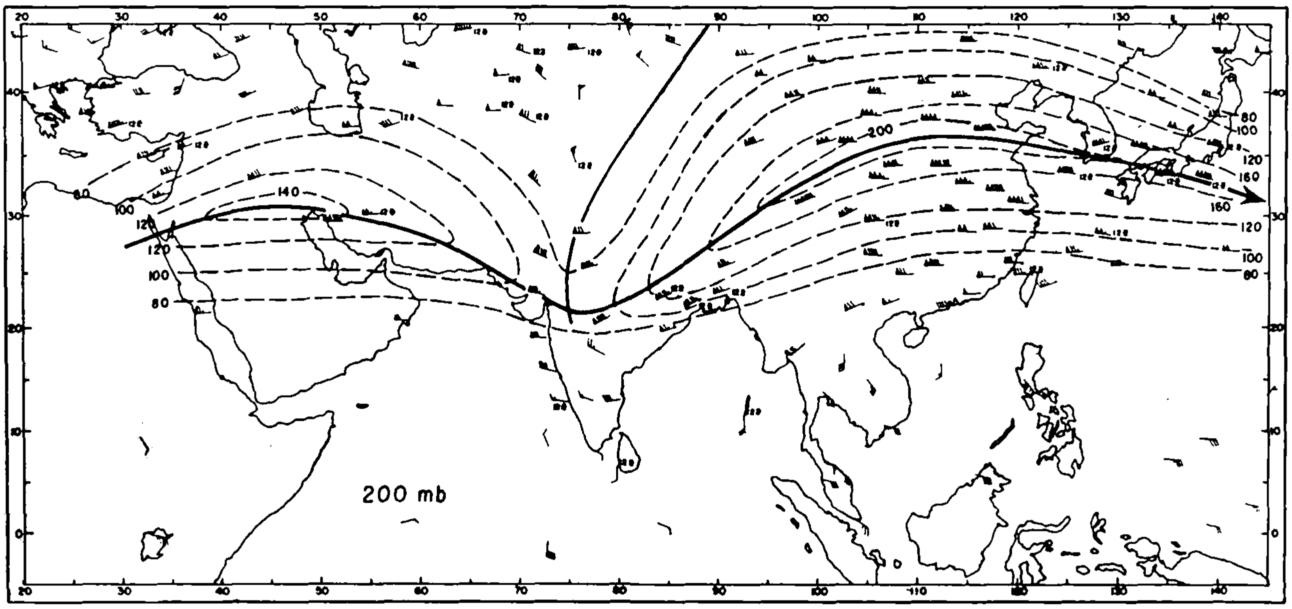
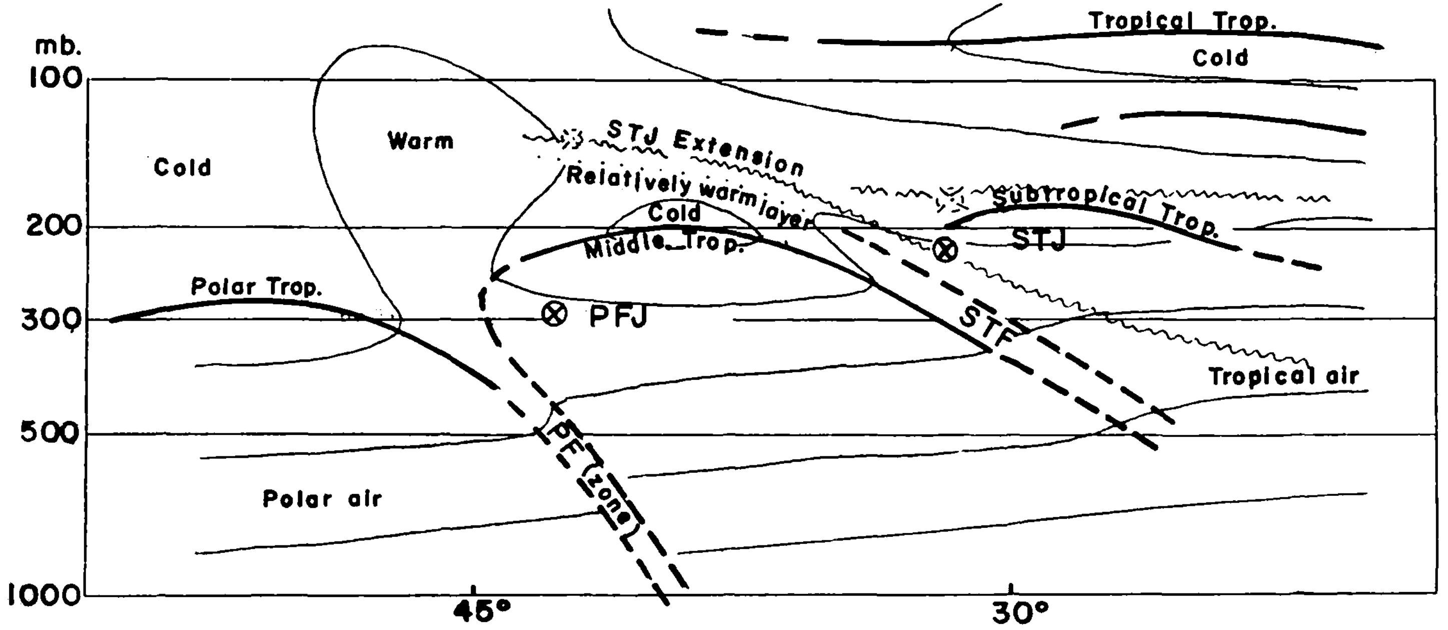


FIG. 7·1

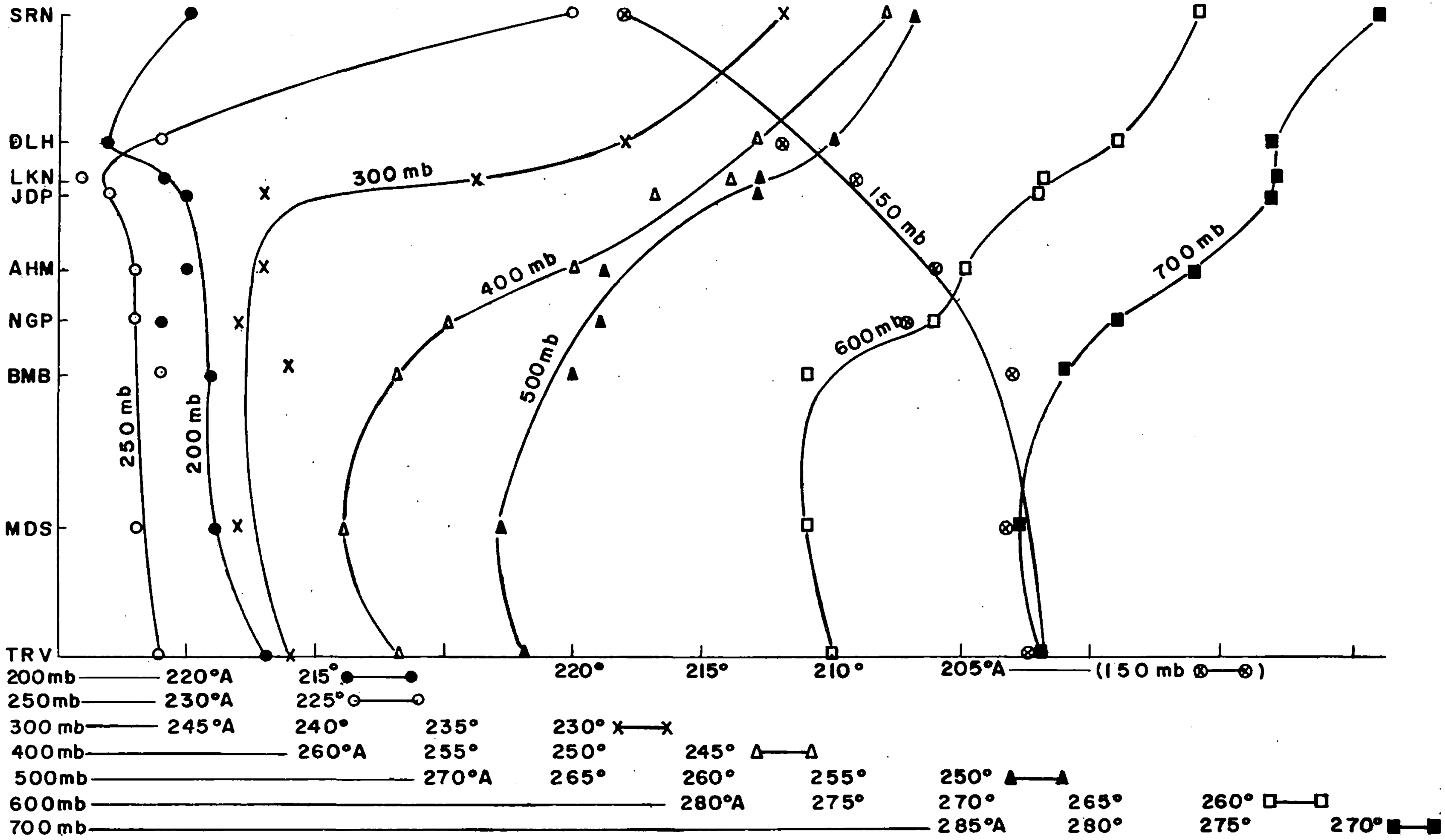
SKETCH OF PRINCIPAL FEATURES OF WIND AND TEMPERATURE FIELDS IN MIDDLE AND SUBTROPICAL LATITUDES (MOST CHARACTERISTIC OF CRESTS OF THE SUBTROPICAL JET STREAM)



PFJ : Polar front jet stream, STJ : Subtropical jet stream(s), STF: Subtropical front
PF : Polar front, Trop : Tropopause

Reproduced from "Structural characteristics of the subtropical jet stream and certain lower-stratospheric wind systems" by Chester W. Newton and Anders V. Persson, Tellus, Vol.14 No.2, pp.221–241 (May, 1962).

FIG. 8·1 TEMPERATURE PROFILE ALONG 80°E ON 21 FEBRUARY 71 (12 GMT)



(Note:- See also fig. 5·5)

FIG. 9·1 MODEL DIAGRAM OF TROPOPAUSE STRUCTURE IN RELATION TO THE JET STREAM

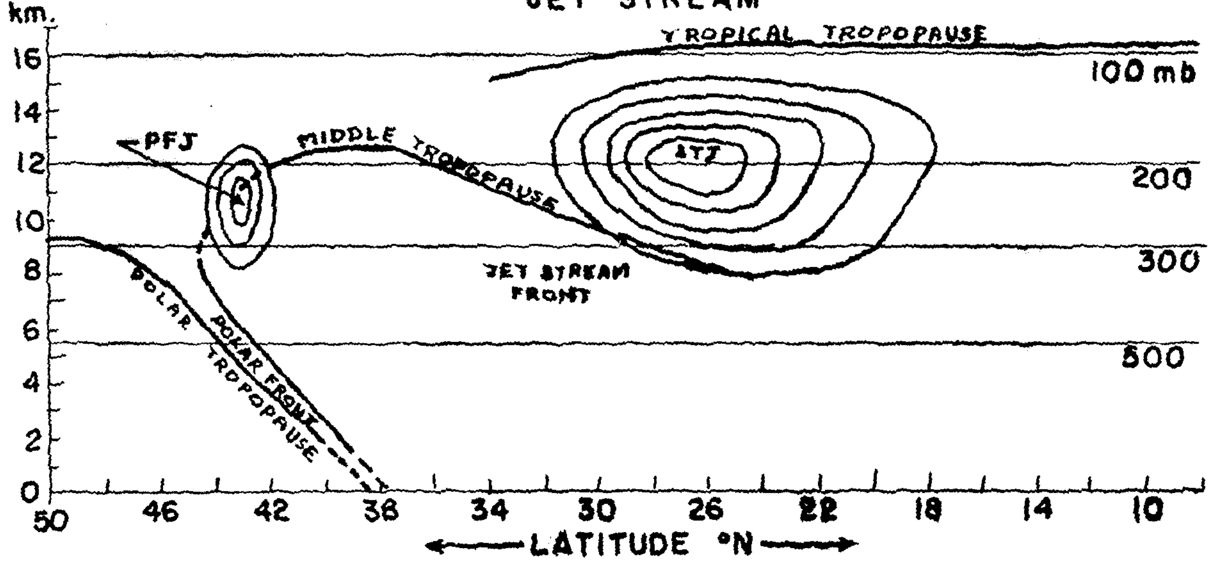
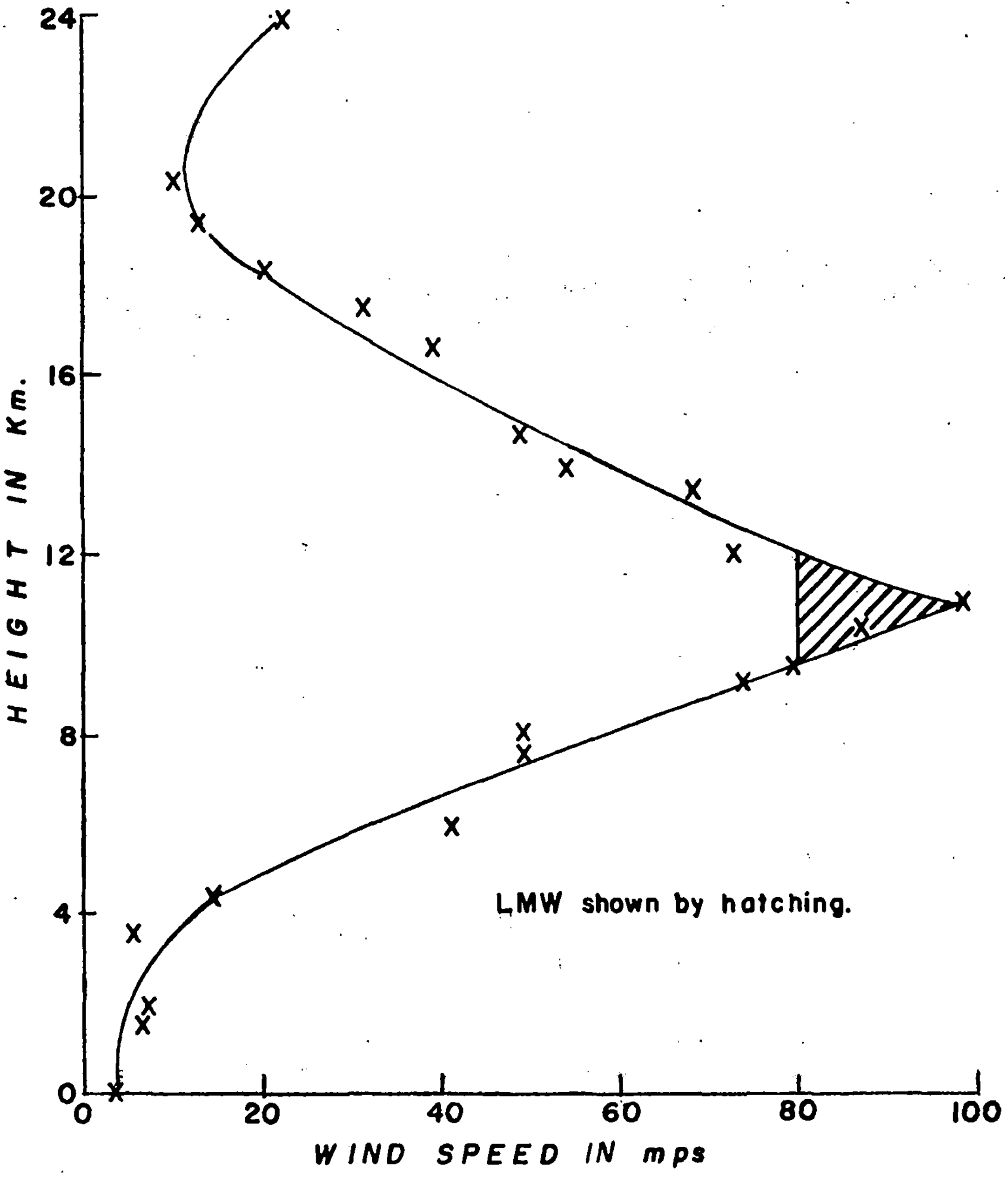


FIG. 10·1 TYPICAL WIND PROFILE : NEW DELHI : 4 FEB. 72 (1200 GMT)



LMW Parameters

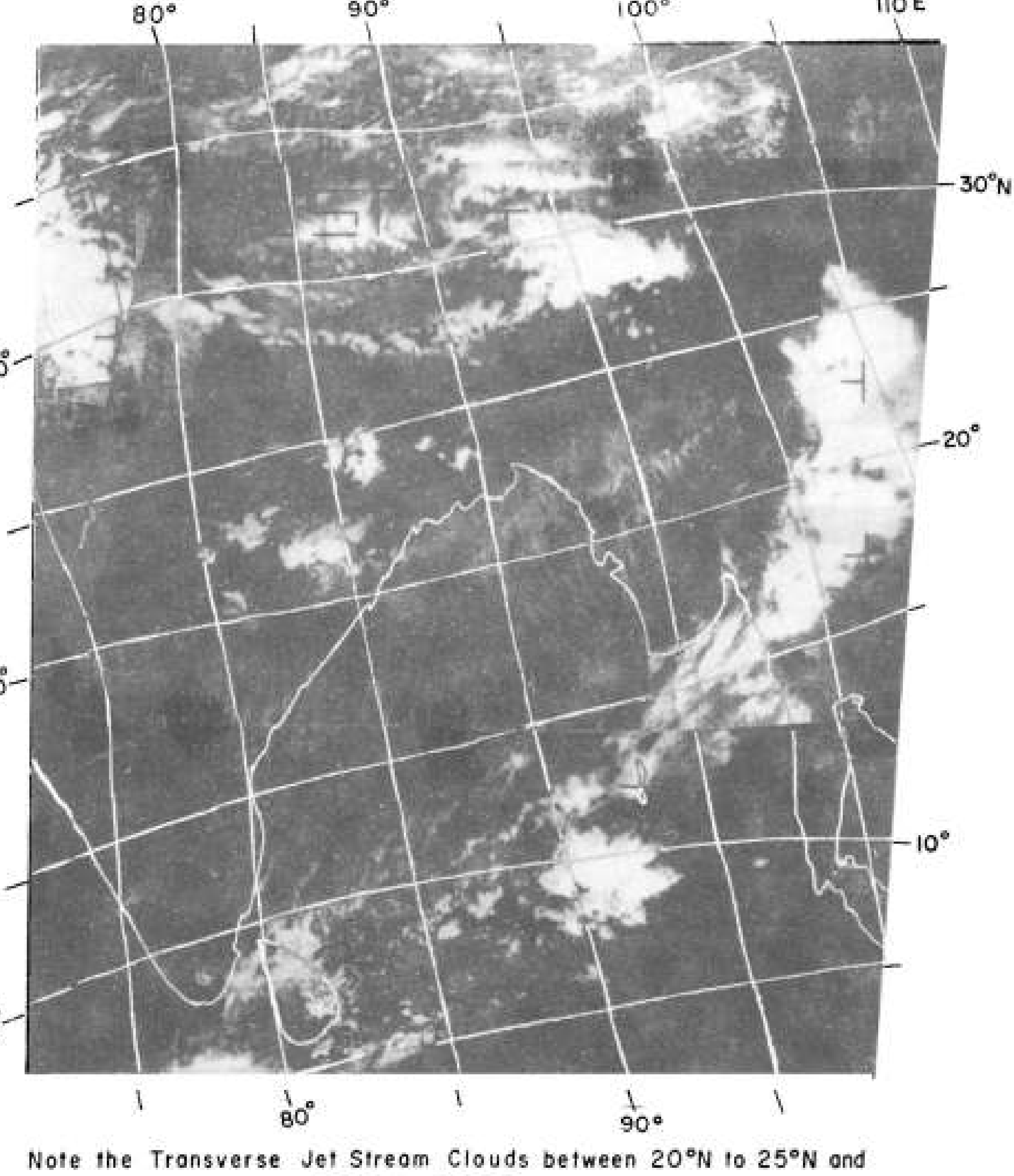
1. Mean wind speed : 90 mps
2. Thickness: 2.5 km
3. Height: 10.9 km
4. Mean Wind Direction: 264°

FIG. II·1 (a)

ESSA - 8

11 JAN. 70

ORBITS 4914 (0336 GMT)
4915 (0530 GMT)



Note the Transverse Jet Stream Clouds between 20°N to 25°N and 85°E to 100°E

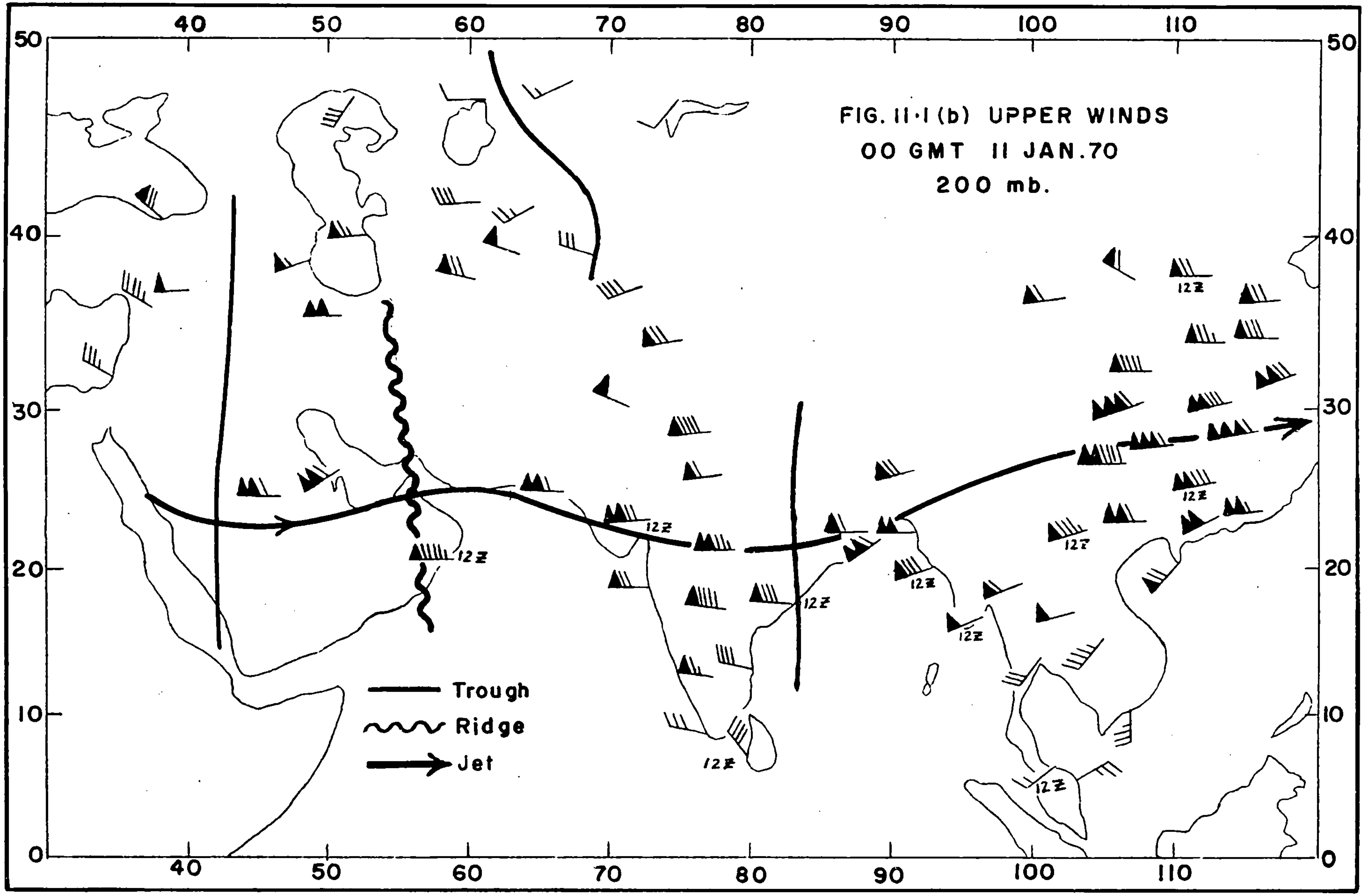
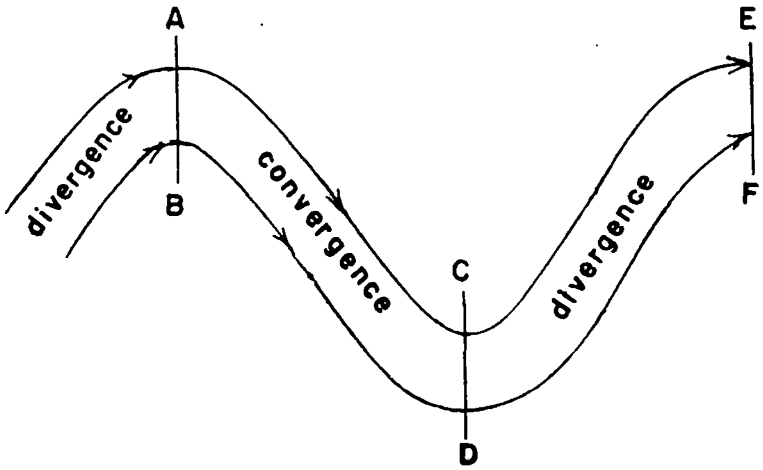


FIG. 11·1 (b) UPPER WINDS
00 GMT 11 JAN.70
200 mb.

FIG.20·1 CONVERGENCE & DIVERGENCE DUE TO CURVATURE IN WAVE PATTERN



Reproduced from "Elements of Dynamic Meteorology" by A.H. Gordon,(Fig.7.7)

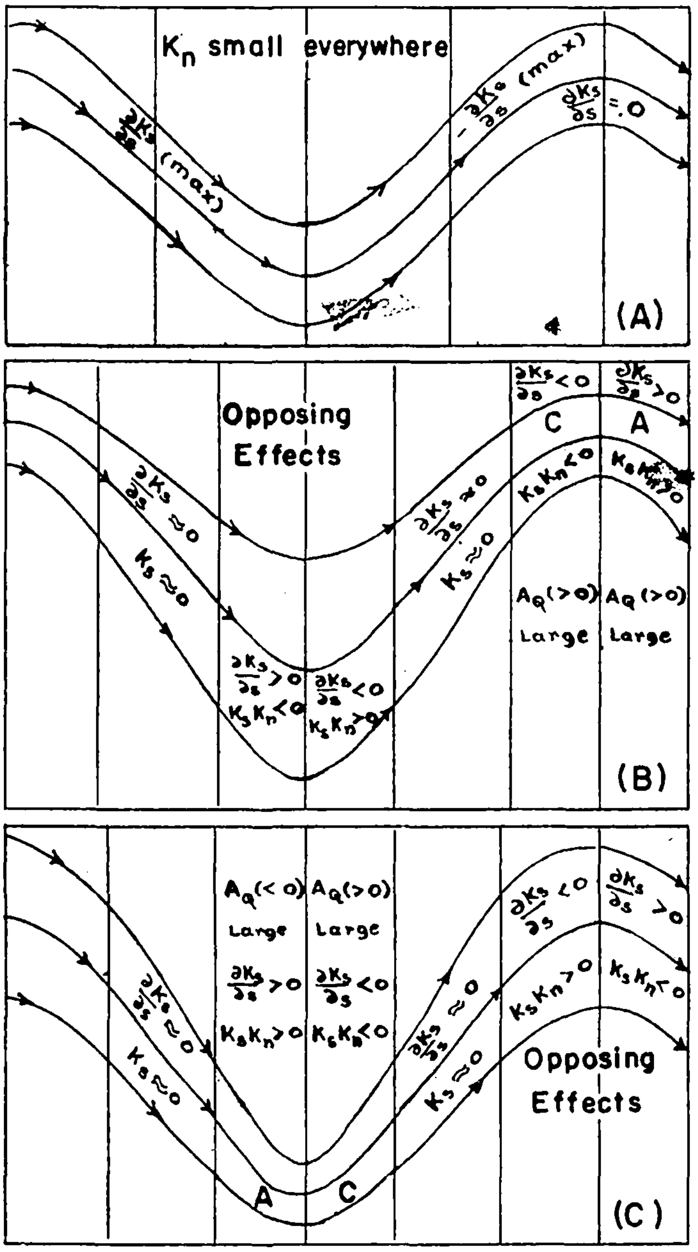
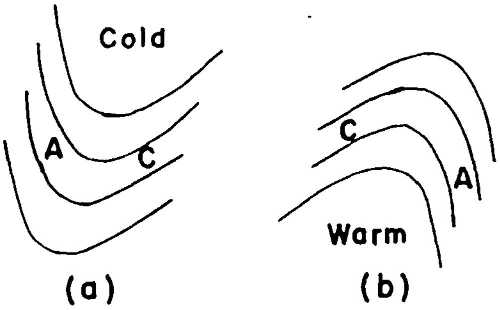


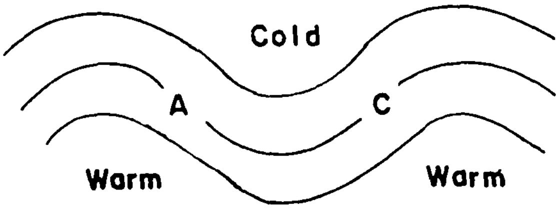
FIG.20·2 SCHEMATIC REPRESENTATION OF THE STREAMLINE CURVATURE ($K_s$) & THE ORTHOGONAL CURVATURE ($K_n$)

Reproduced from "Weather Analysis and Forecasting", Vol.I by Sverre Petterssen, 1956 (Fig. 16.6.1)

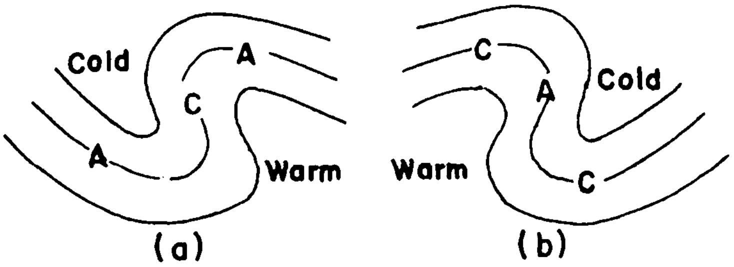
# FIG.21·1 TYPICAL THICKNESS PATTERNS & THEIR CHARACTERISTIC FEATURES



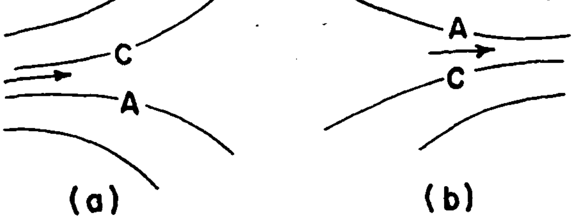
(a) The cold thermal trough; (b) The warm thermal ridge. Cyclonic development, C, occurs forward of the thermal trough, behind the thermal ridge; anticyclonic development, A, on the opposite sides.



The sinusoidal thermal pattern. Cyclonic development is centred at the pre-trough inflexion, anticyclonic at the pre-ridge inflexion. With small amplitude wave-form, thermal steering is dominant and the situation travels in a wave-like manner.

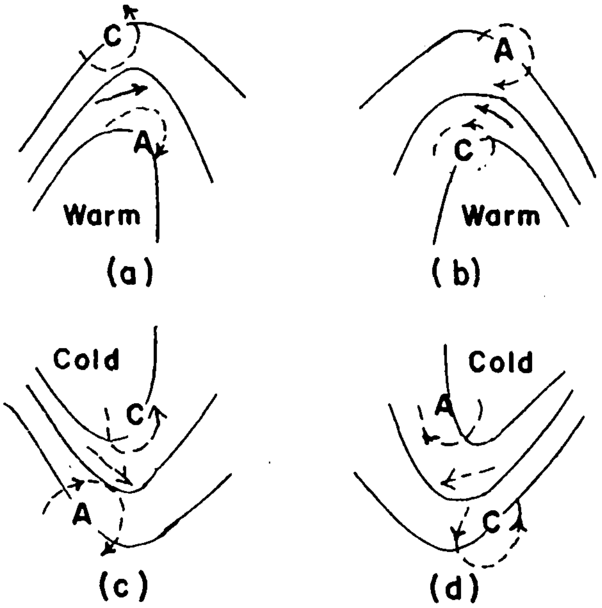


(a) The cyclonic involution; (b) The anticyclonic involution. These patterns are distortions of the sinusoidal perturbations usually produced by depressions or anticyclones in the appropriate development regions. They are self-developing.

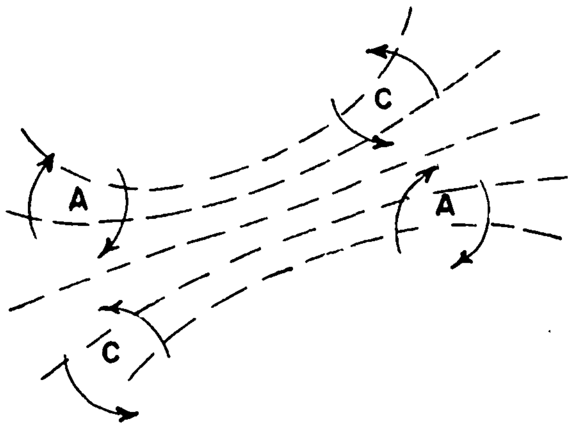


(a) The difluent thermal jet; (b) The confluent thermal jet. Cyclonic development is a feature of the left exit and right entrance of the thermal jet, anticyclonic development on the opposite sides.

## FIG. 21·1 (Contd) TYPICAL THICKNESS PATTERNS & THEIR CHARACTERISTIC FEATUR



Combinations of thermal ridge and trough with difluence and confluence.
(a) The difluent thermal ridge; (b) The confluent thermal ridge;
(c) The difluent thermal trough; (d) The confluent thermal trough.



The thermal jet complex. The development regions favour the existence of depressions in the C regions and anticyclones in the A regions, which tend to distort the thermal pattern by advection and maintain or develop the jet structure. This is the hyperbolic frontogenetic complex which is self-developing.

Reproduced from QJRMS, Vol.76 1950, pp.189-217.
"The Theory and use of upper air thickness patterns in forecasting" by R.C. Sutcliffe and A.G. Forsdyke.

FIG. 25·1 (a) SEA LEVEL CHART 1200 GMT 19 JANUARY 1973

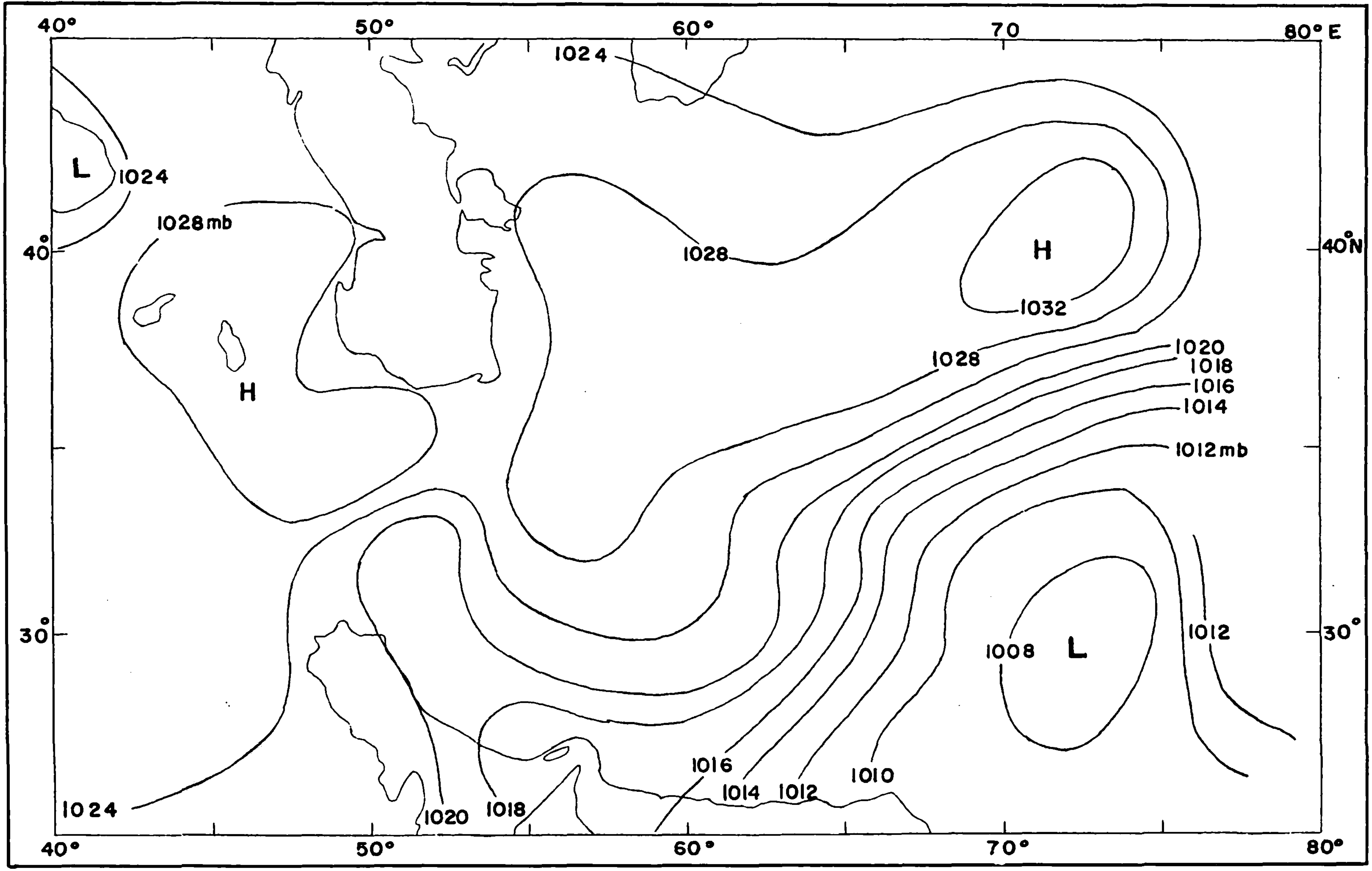


FIG. 25·1 (b) UPPER AIR CHART 1200 GMT 19 JANUARY 73 500mb

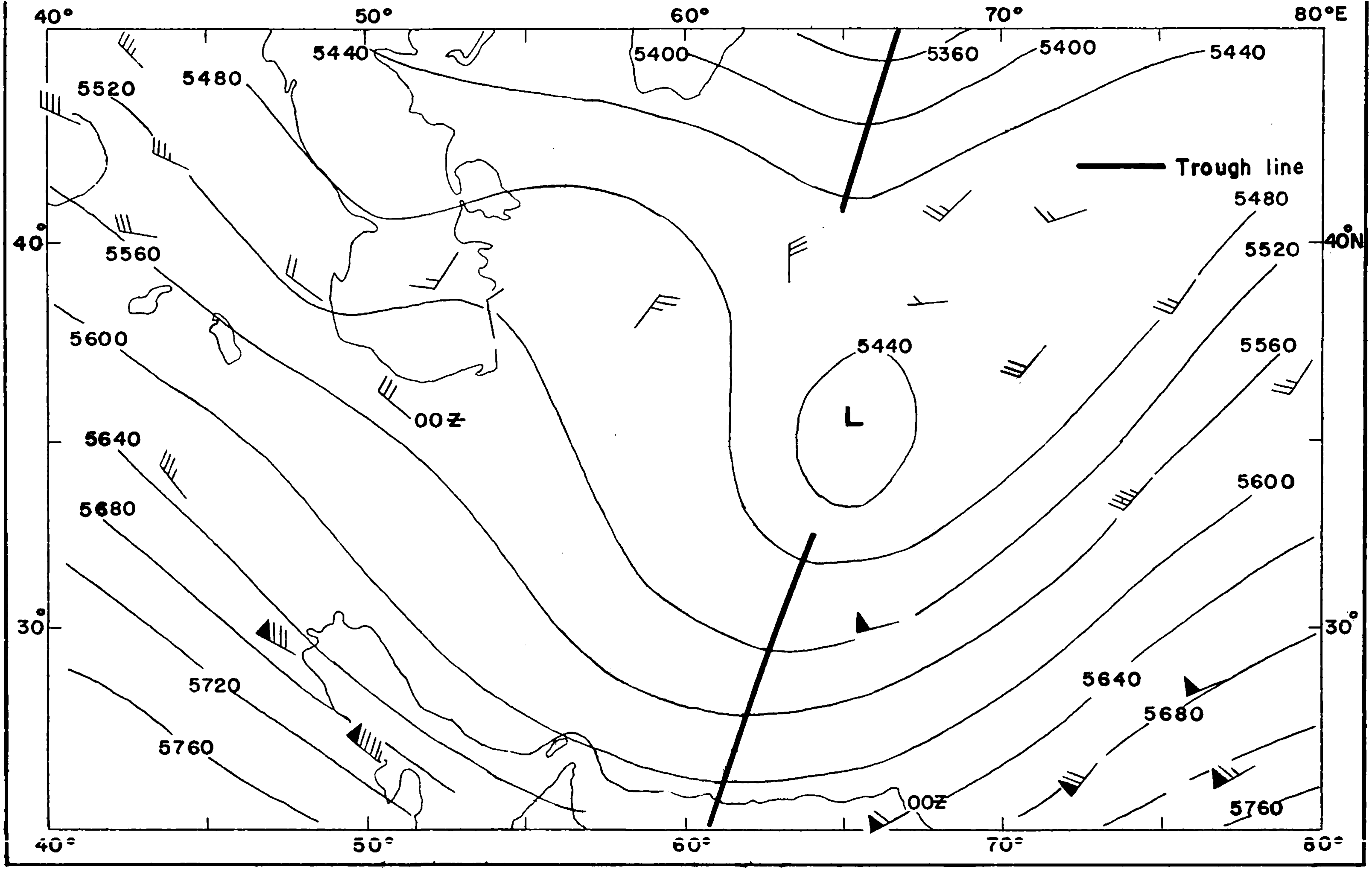
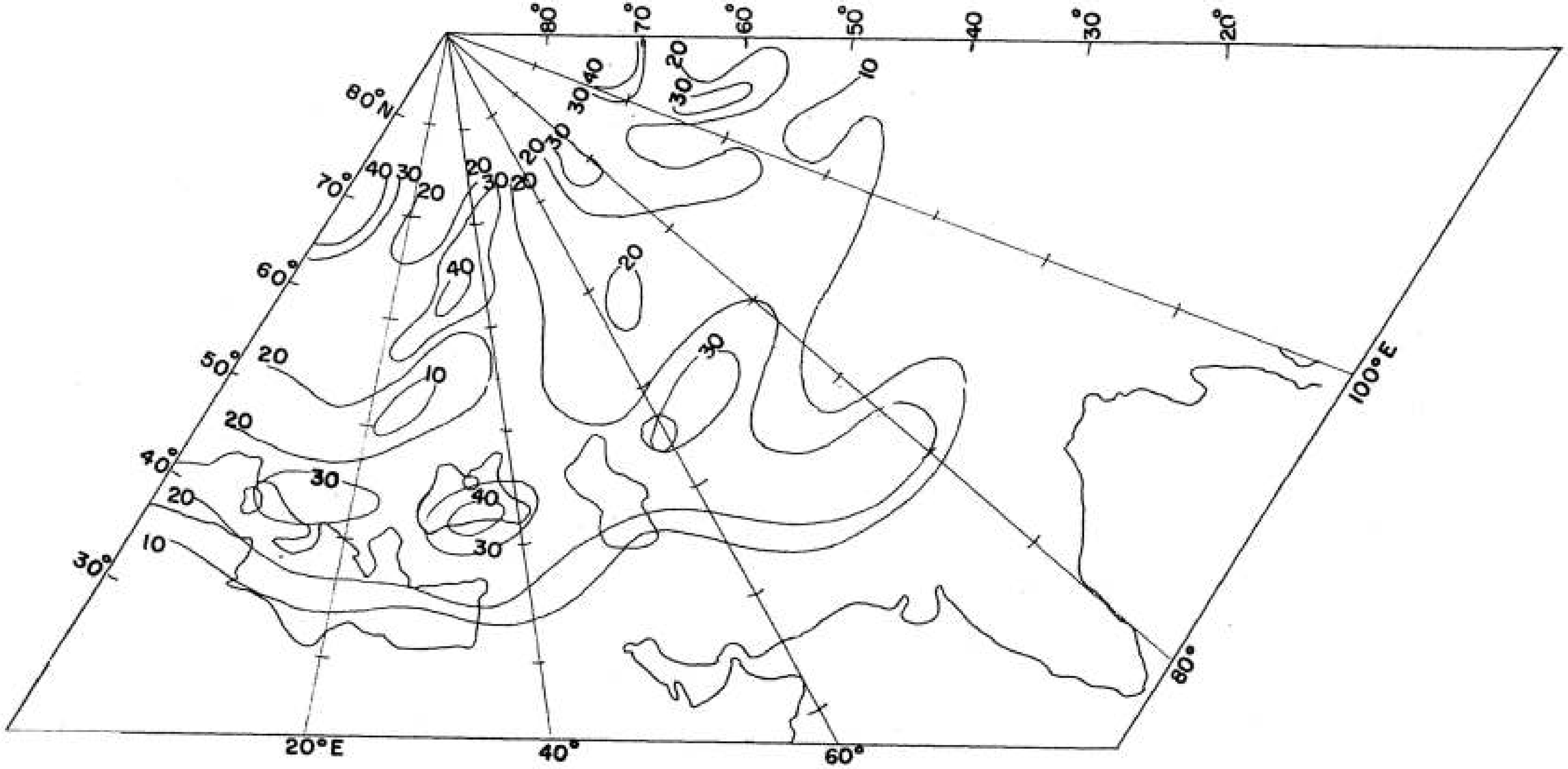


FIG. 29·1 Distribution of positions of closed lows on 500mb chart during winter
(Based on data of Dec., Jan. & Feb. of 1967 - 1969)



# FIG. 30·1(a) UPPER WINDS 0000 GMT 23 DEC. 69

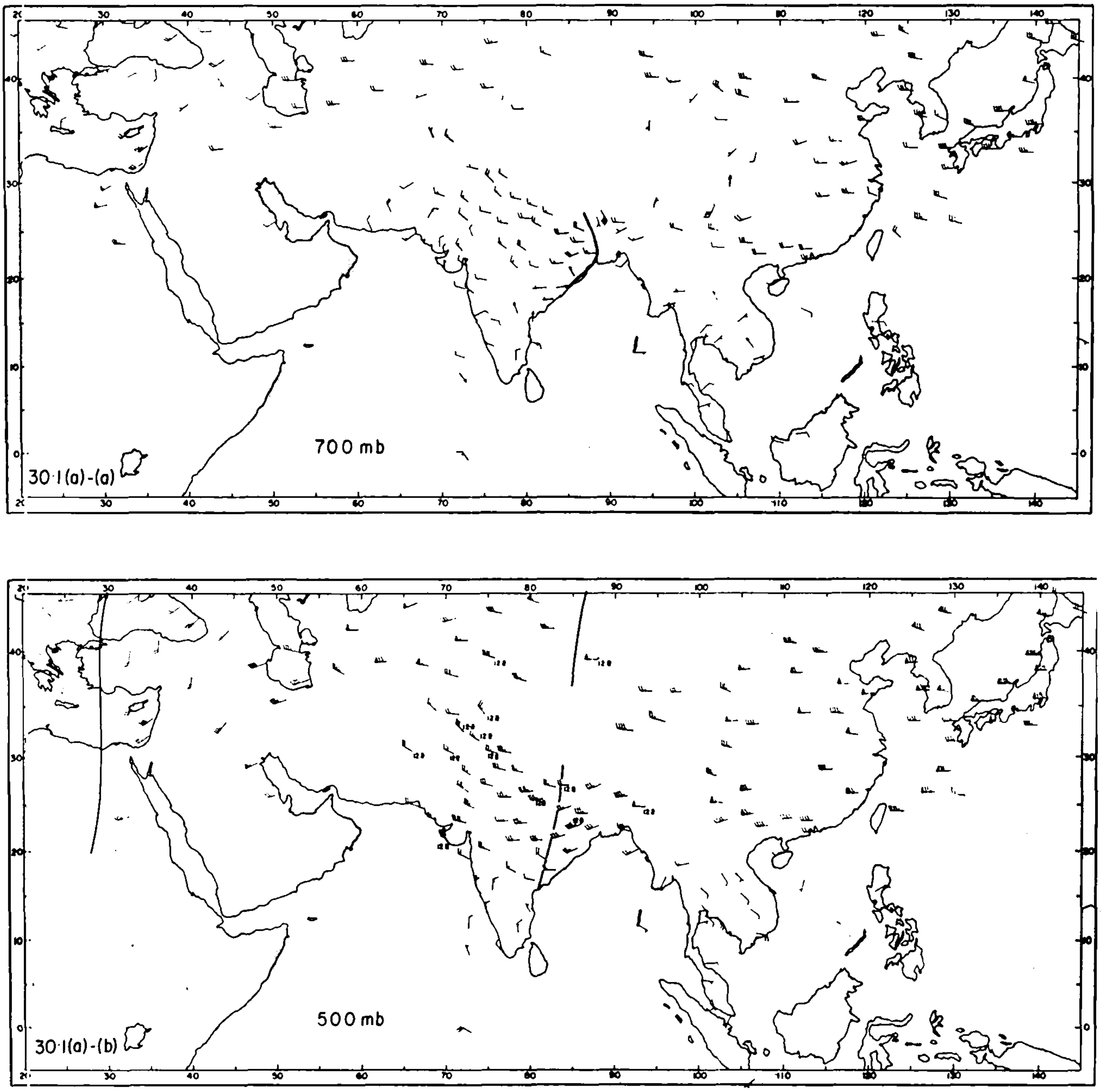


FIG. 30·1(b) UPPER WINDS 0000 GMT 23 DEC. 69

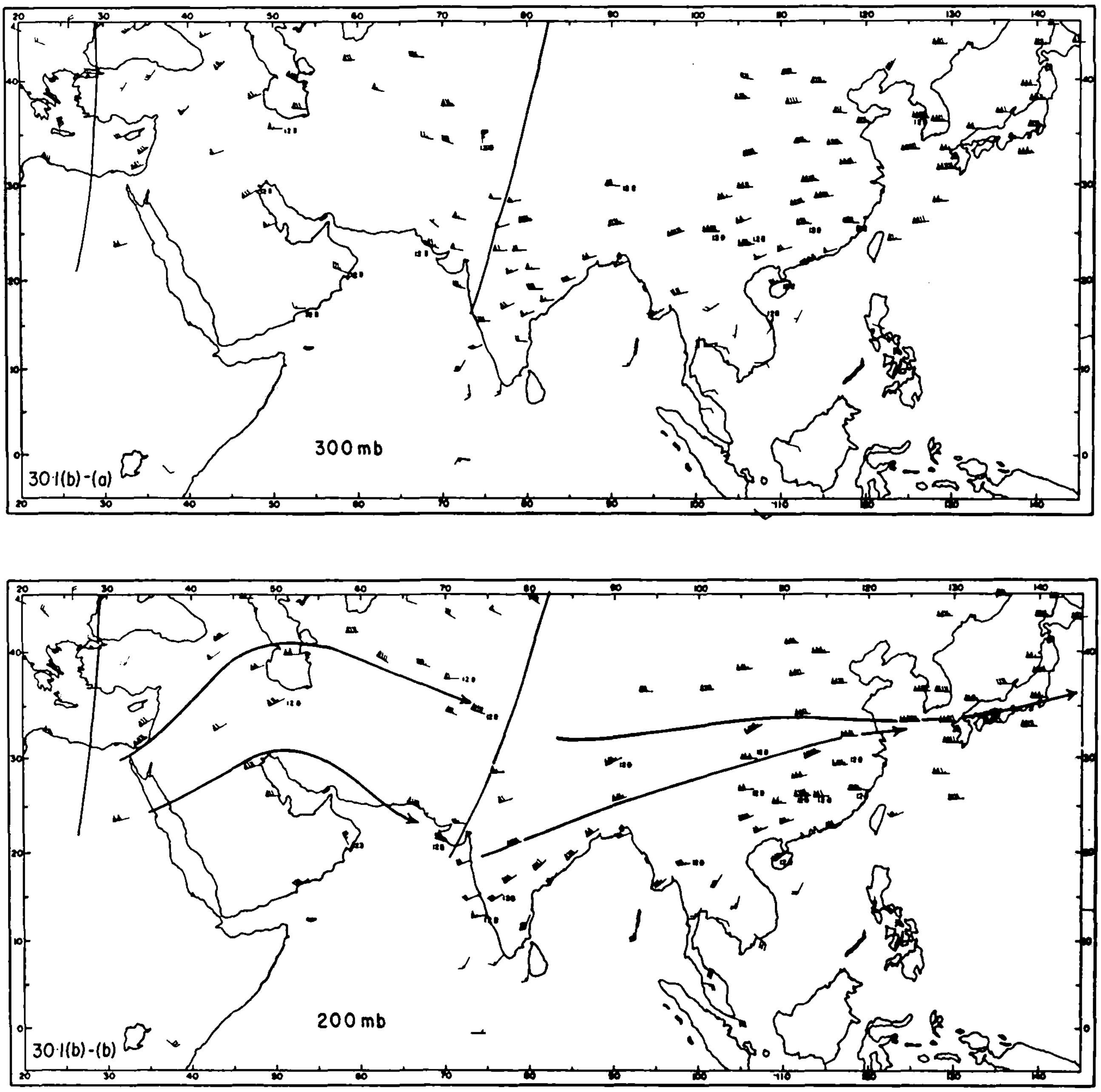


FIG. 31·1 UPPER WINDS 1200 GMT 8 JAN. 71

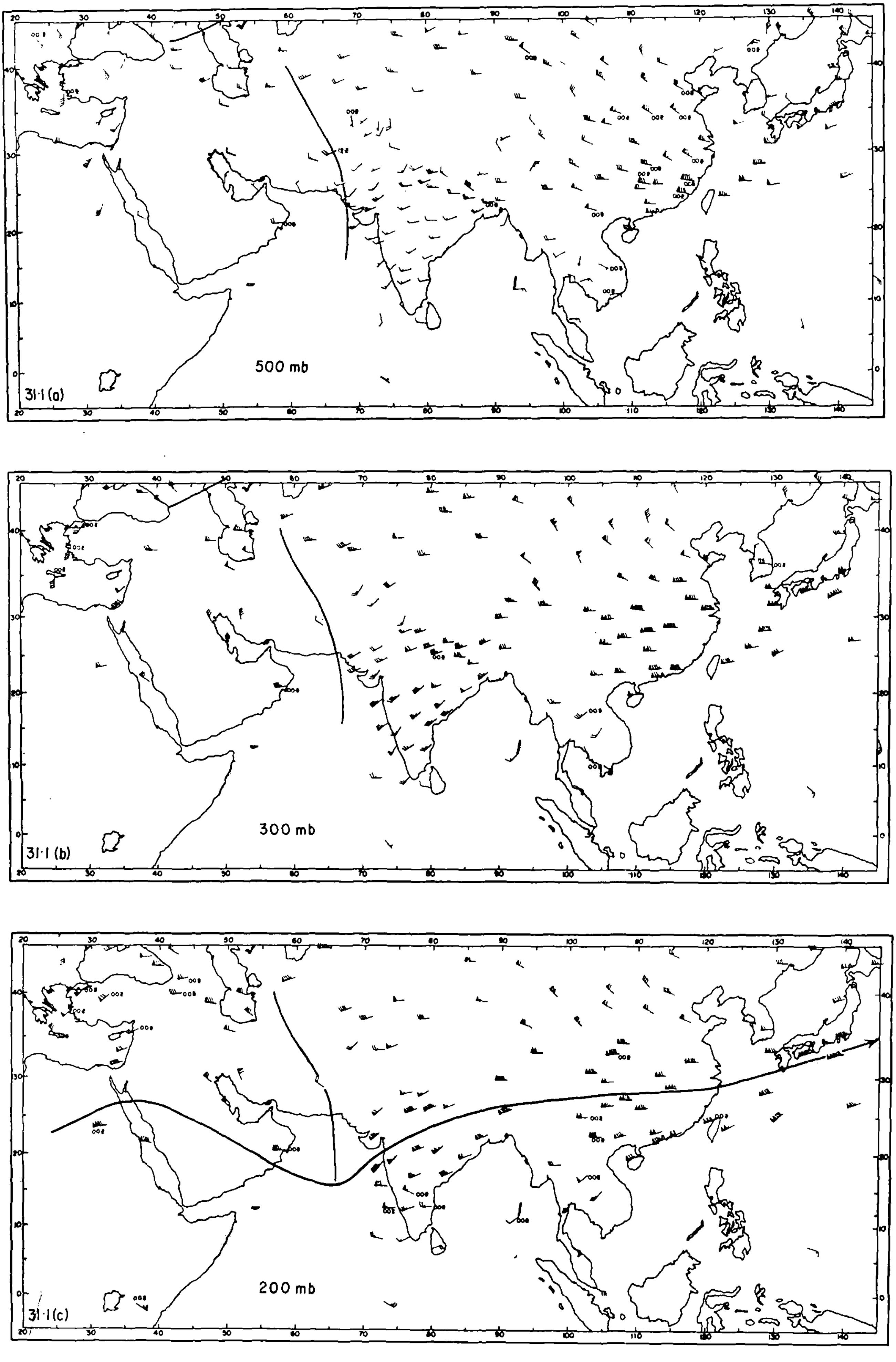


FIG. 31·2 UPPER WINDS 1200 GMT 10 JAN. 71

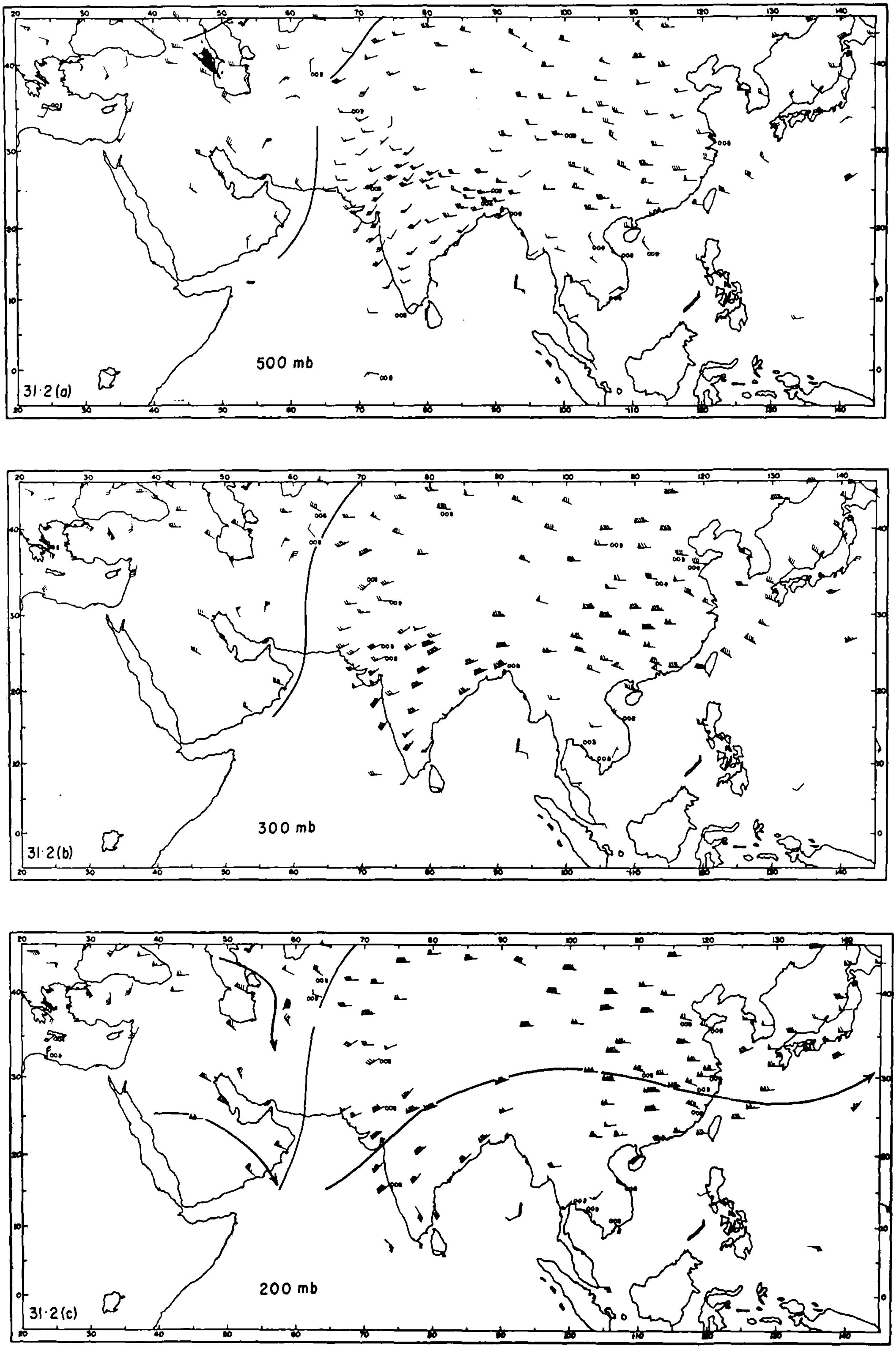
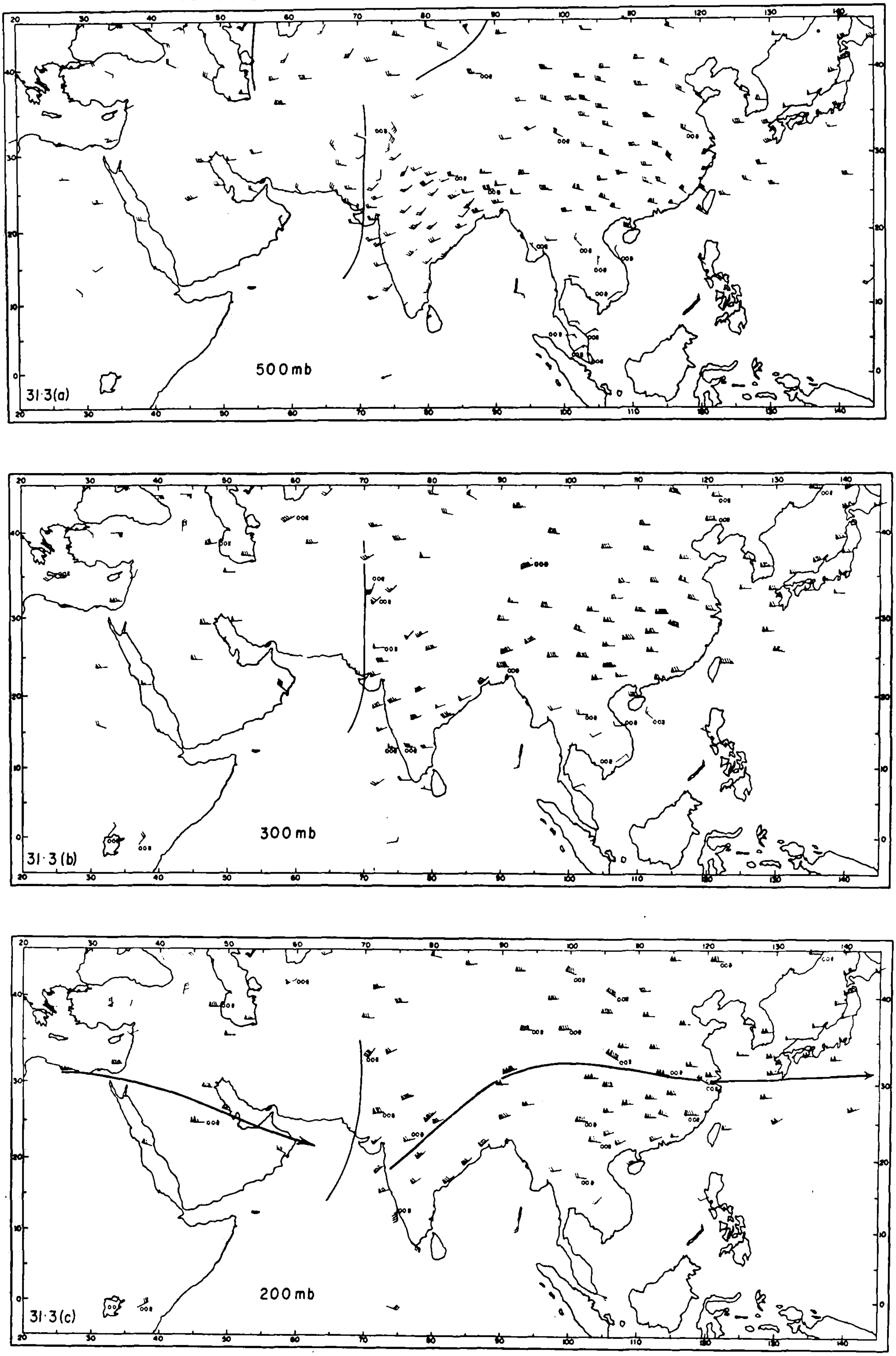


FIG. 31·3 UPPER WINDS 1200 GMT 11 JAN. 71



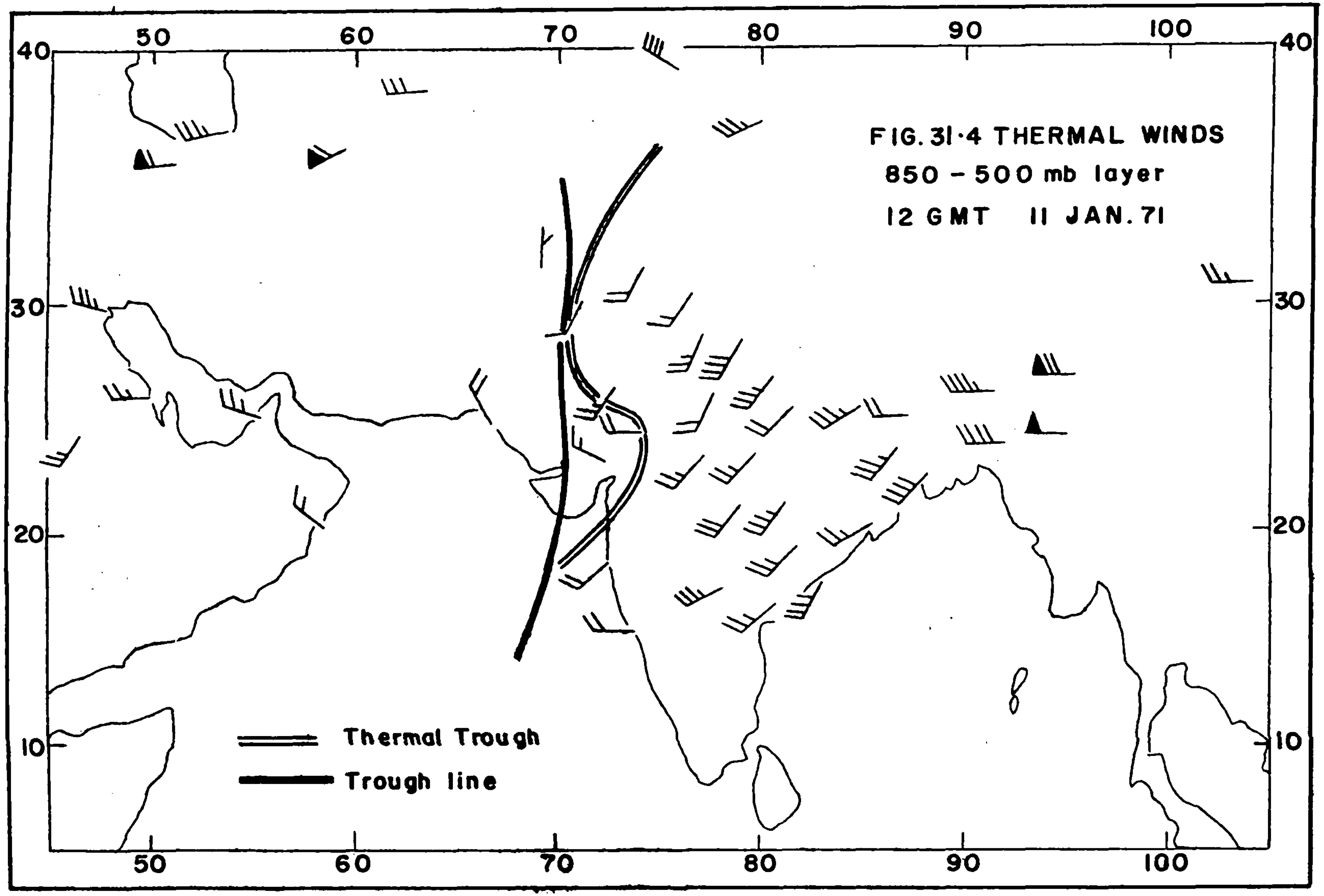
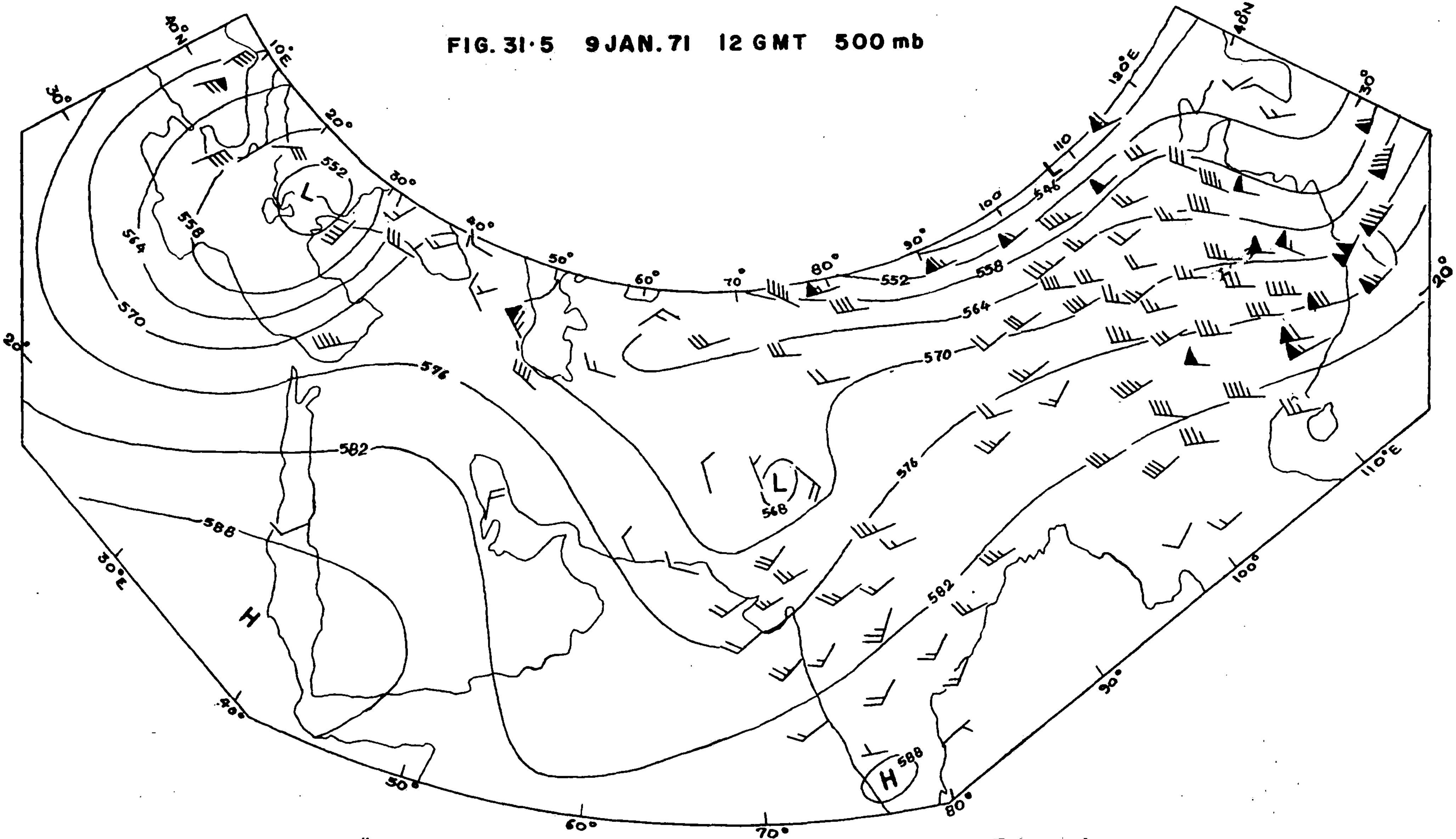


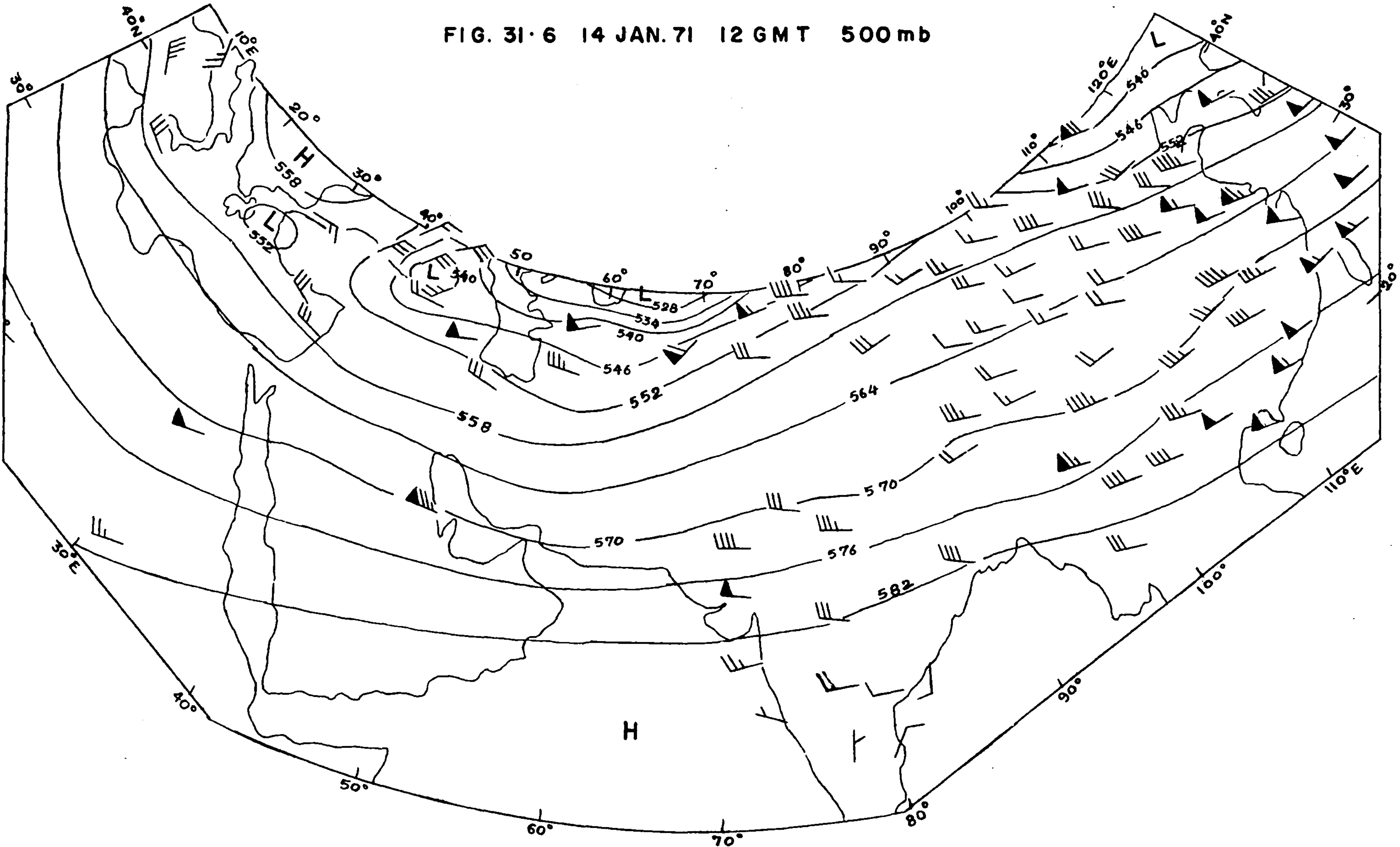
FIG. 31·4 THERMAL WINDS
850 - 500 mb layer
12 GMT 11 JAN. 71

FIG. 31·5 9 JAN. 71 12 GMT 500 mb



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

FIG. 31·6 14 JAN. 71 12 GMT 500mb



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

FIG. 31·7(a) VERTICAL CROSS SECTION : 00 GMT 9 JAN. 71

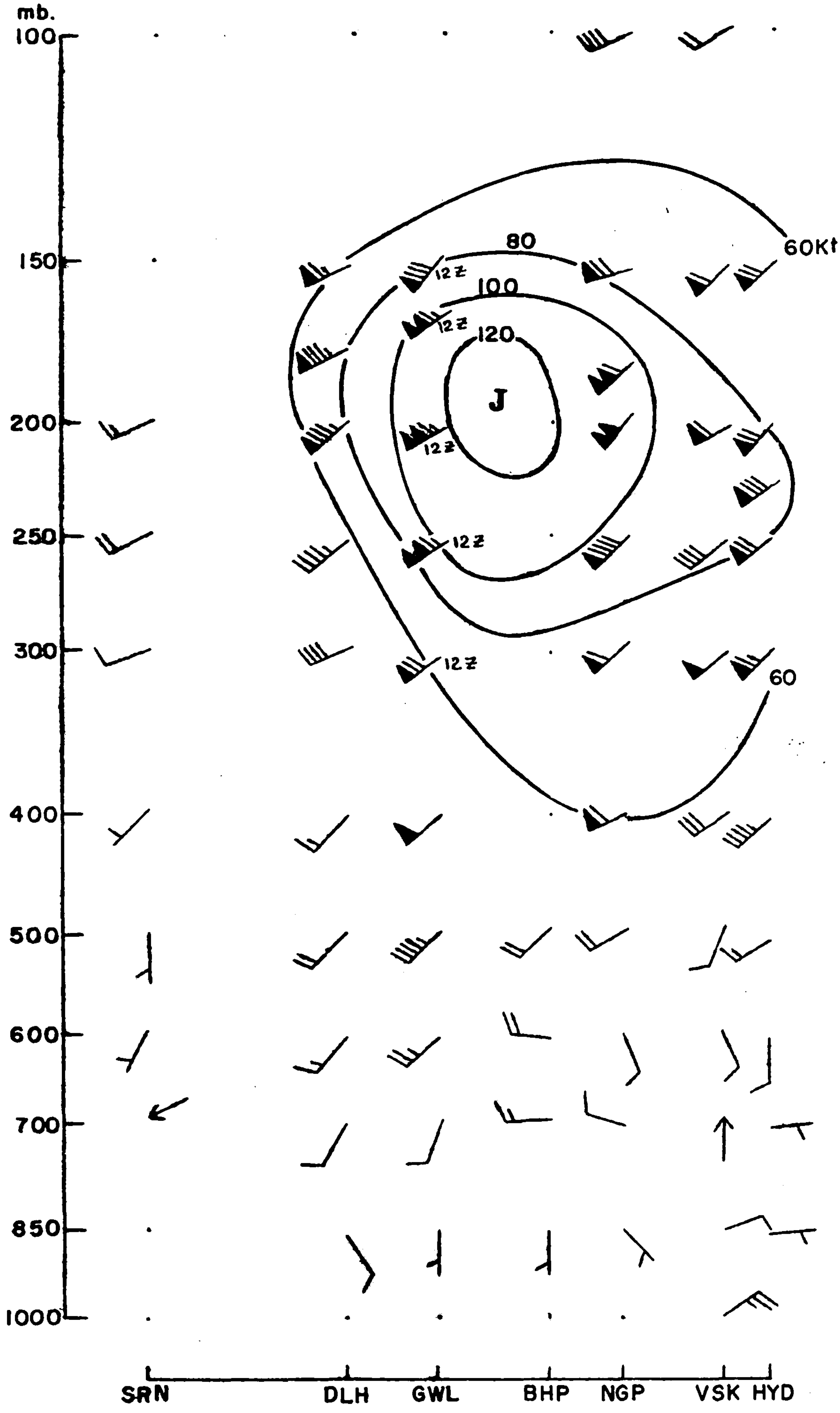


FIG. 31·7 (b) VERTICAL CROSS SECTION : 00 GMT 9 JAN. 71

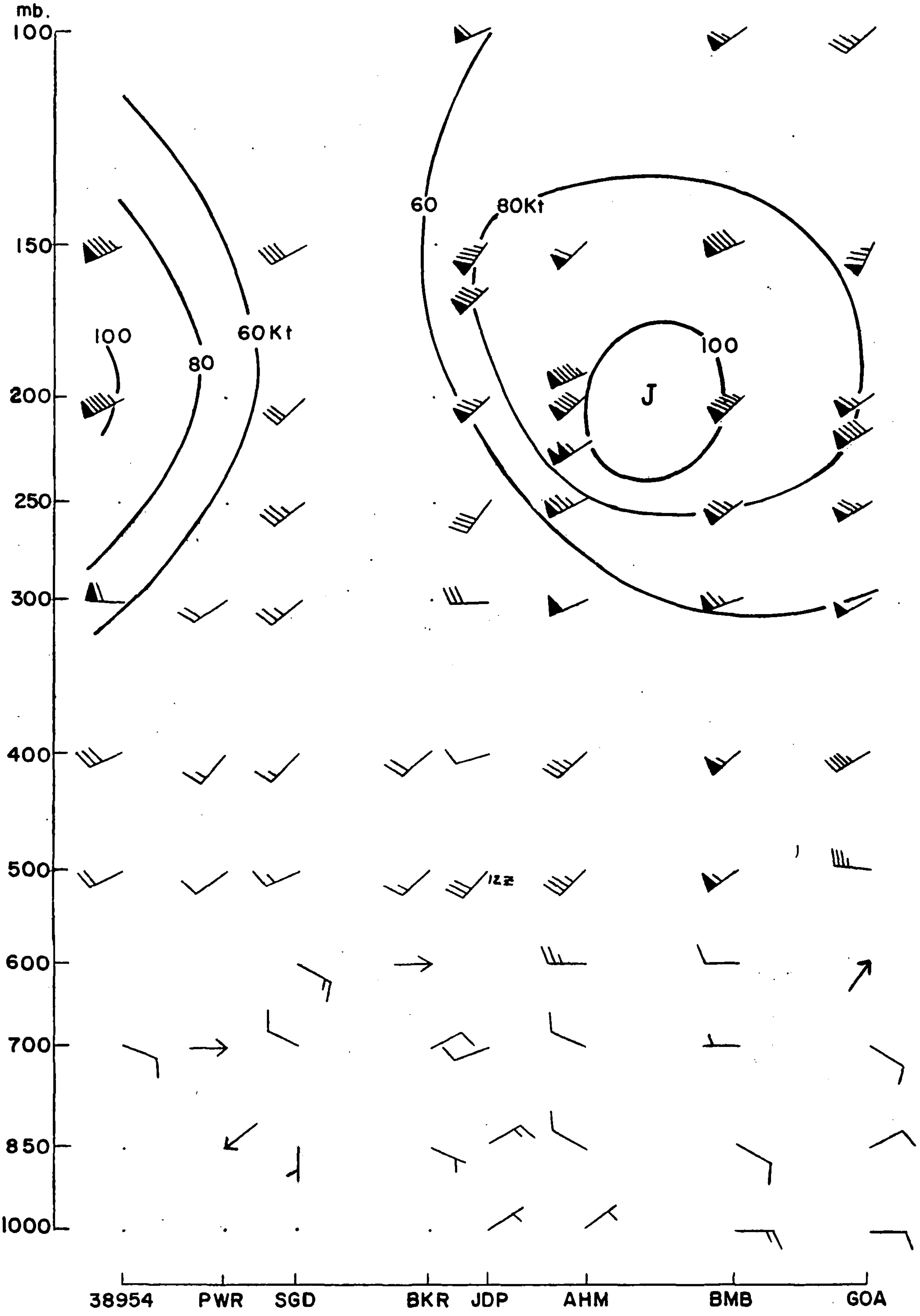


FIG. 32·1 UPPER WINDS 0000 GMT 19 JAN. 70

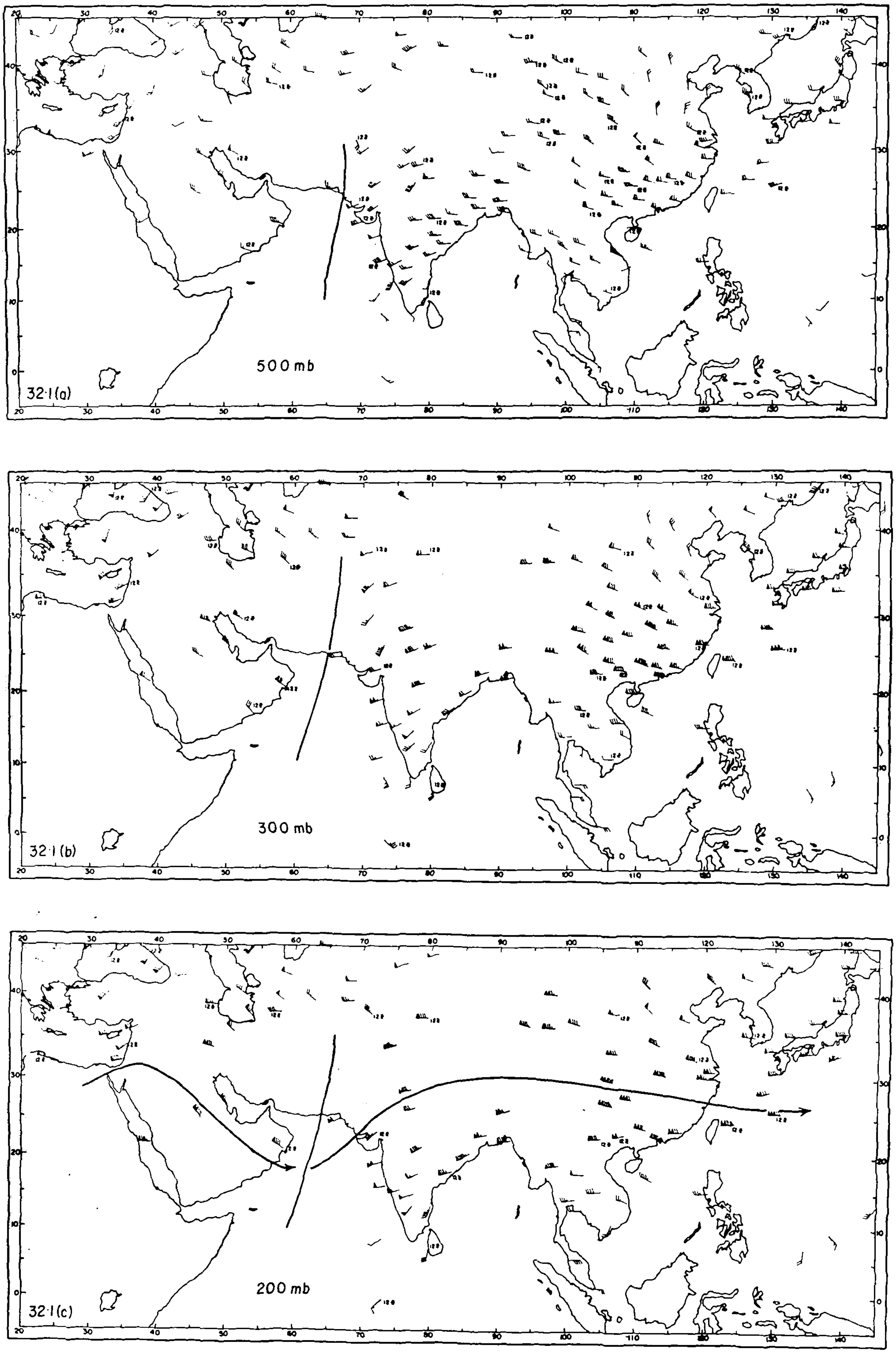


FIG. 32·2 UPPER WINDS 0000 GMT 20 JAN. 70

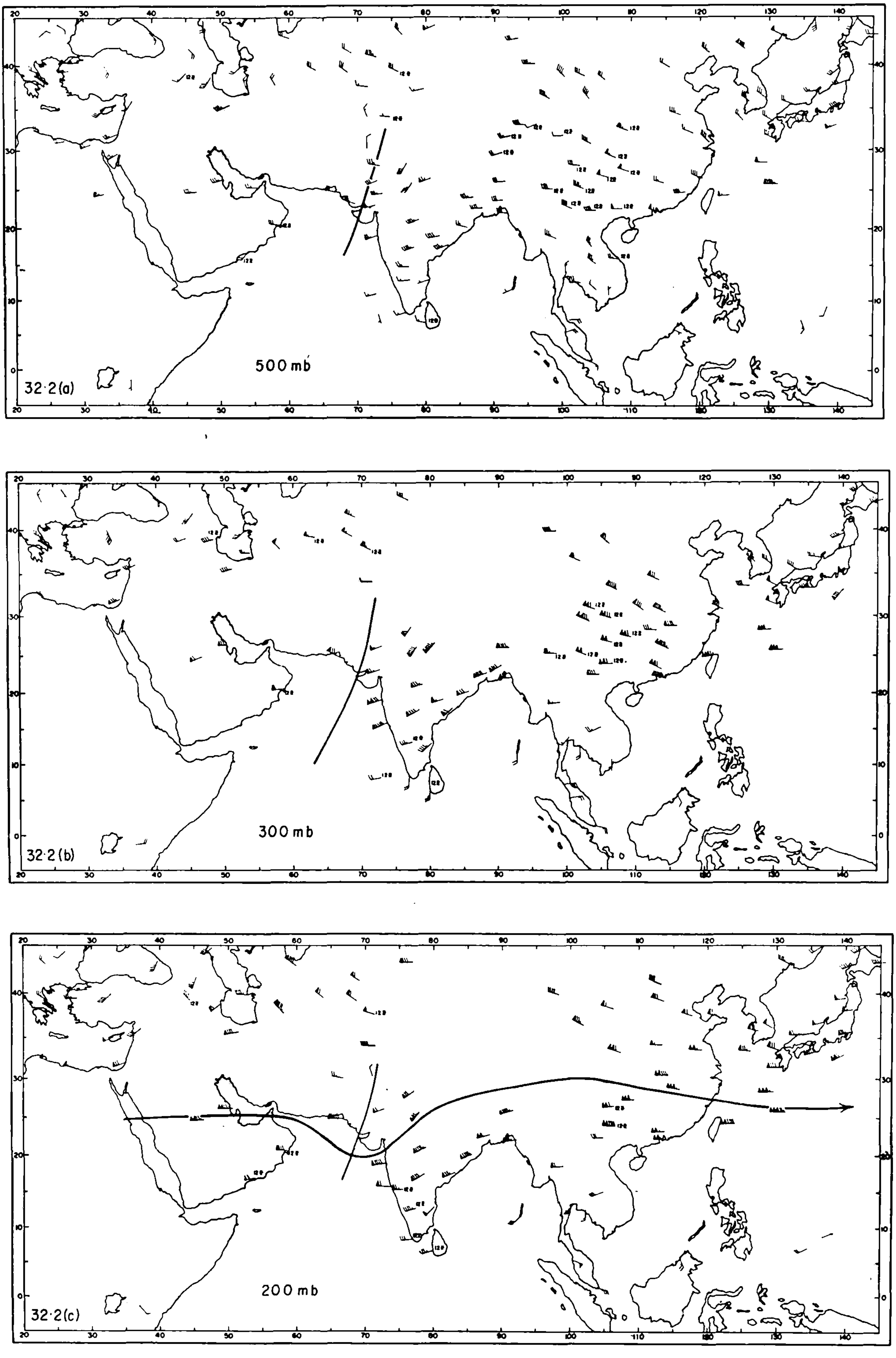
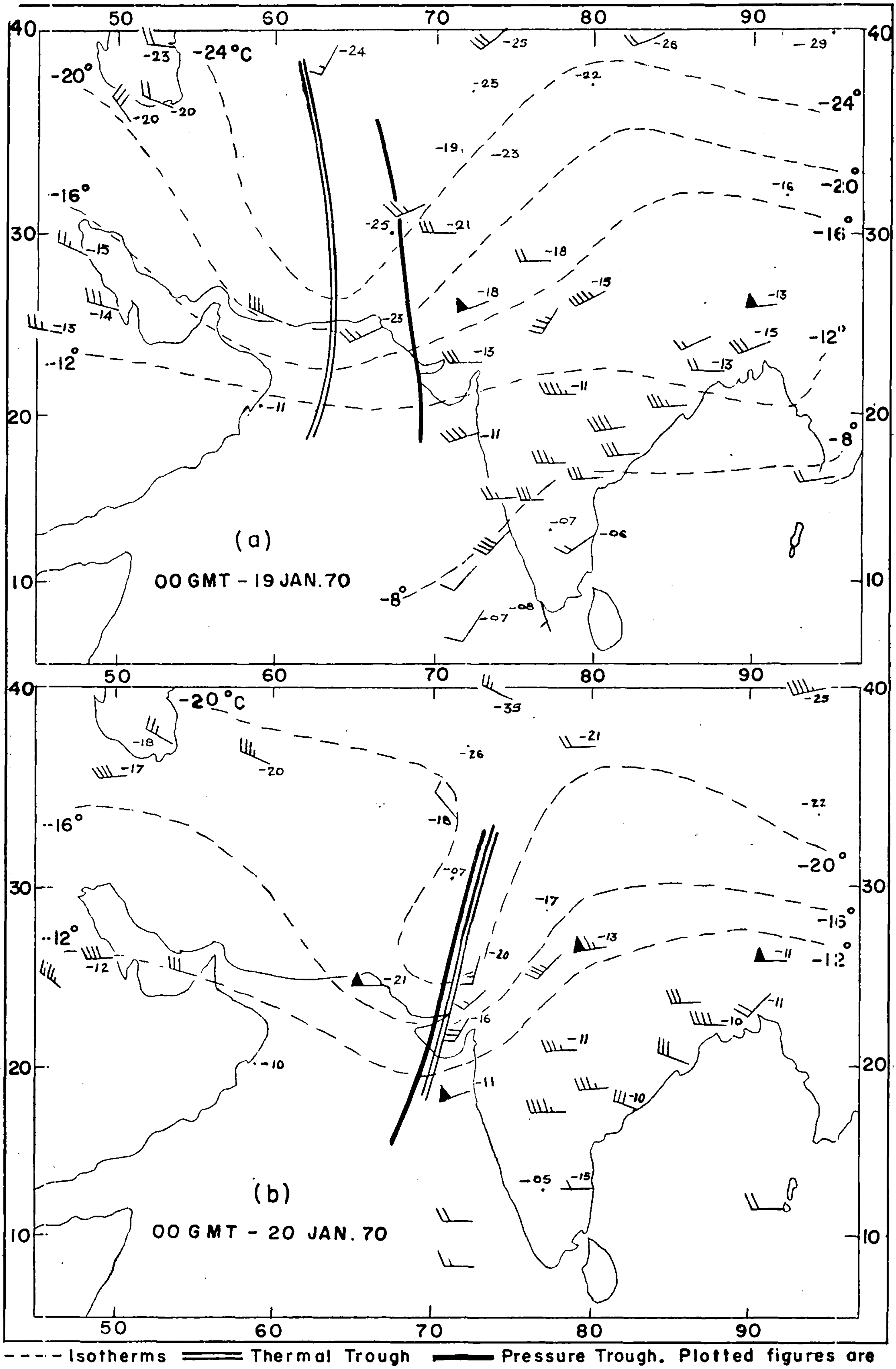
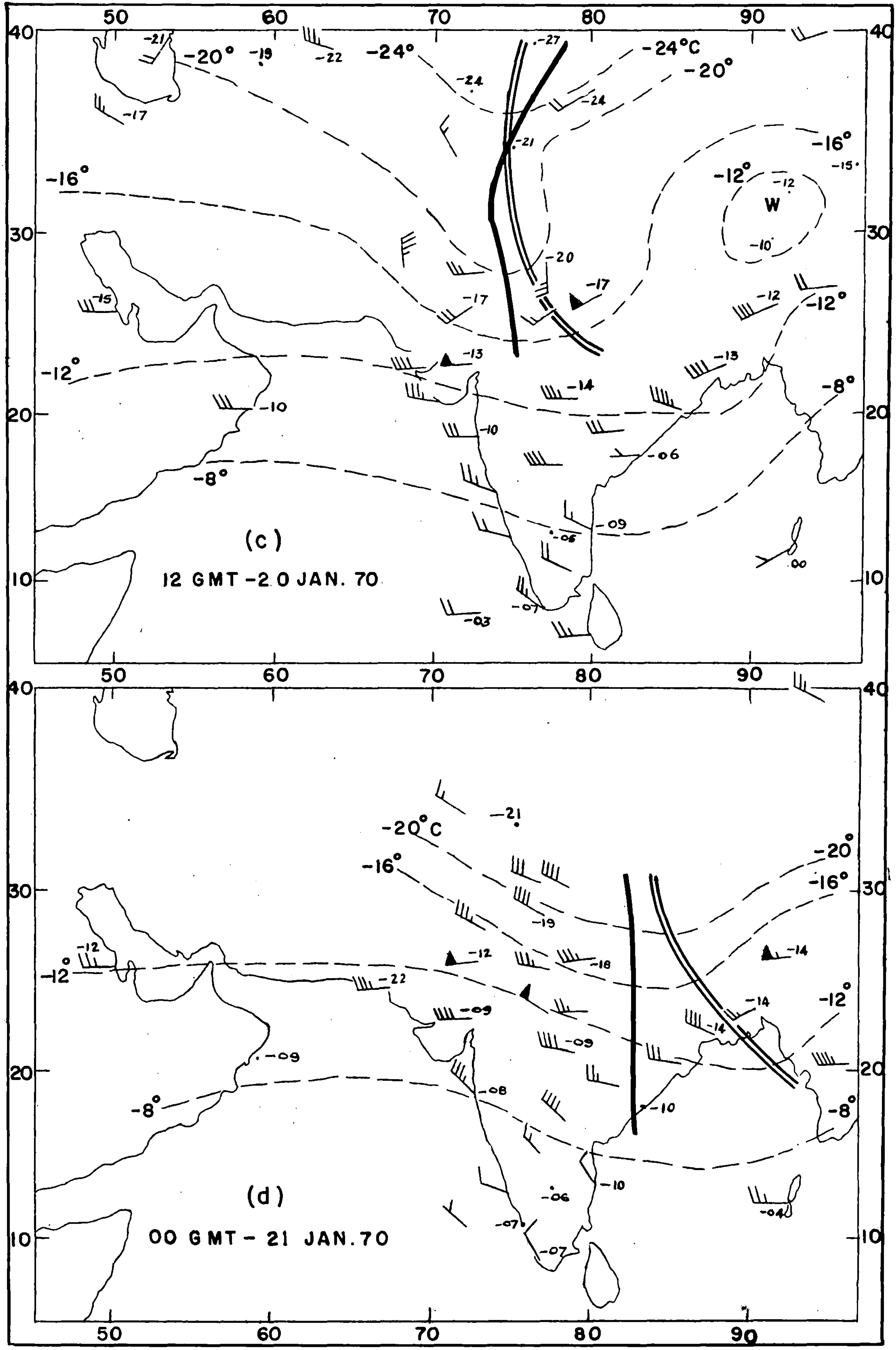


FIG. 32·3 THERMAL WINDS : LAYER 850 - 500 mb



---- Isotherms ═══ Thermal Trough ━━━ Pressure Trough. Plotted figures are temperatures at 500 mb

FIG. 32·3 THERMAL WINDS : LAYER 850-500 mb



----Isotherms ══ Thermal Trough ━━ Pressure Trough. Plotted figures are -temperatures at 500 mb

FIG. 32·4 VERTICAL CROSS SECTION: 00GMT 20 JAN.70

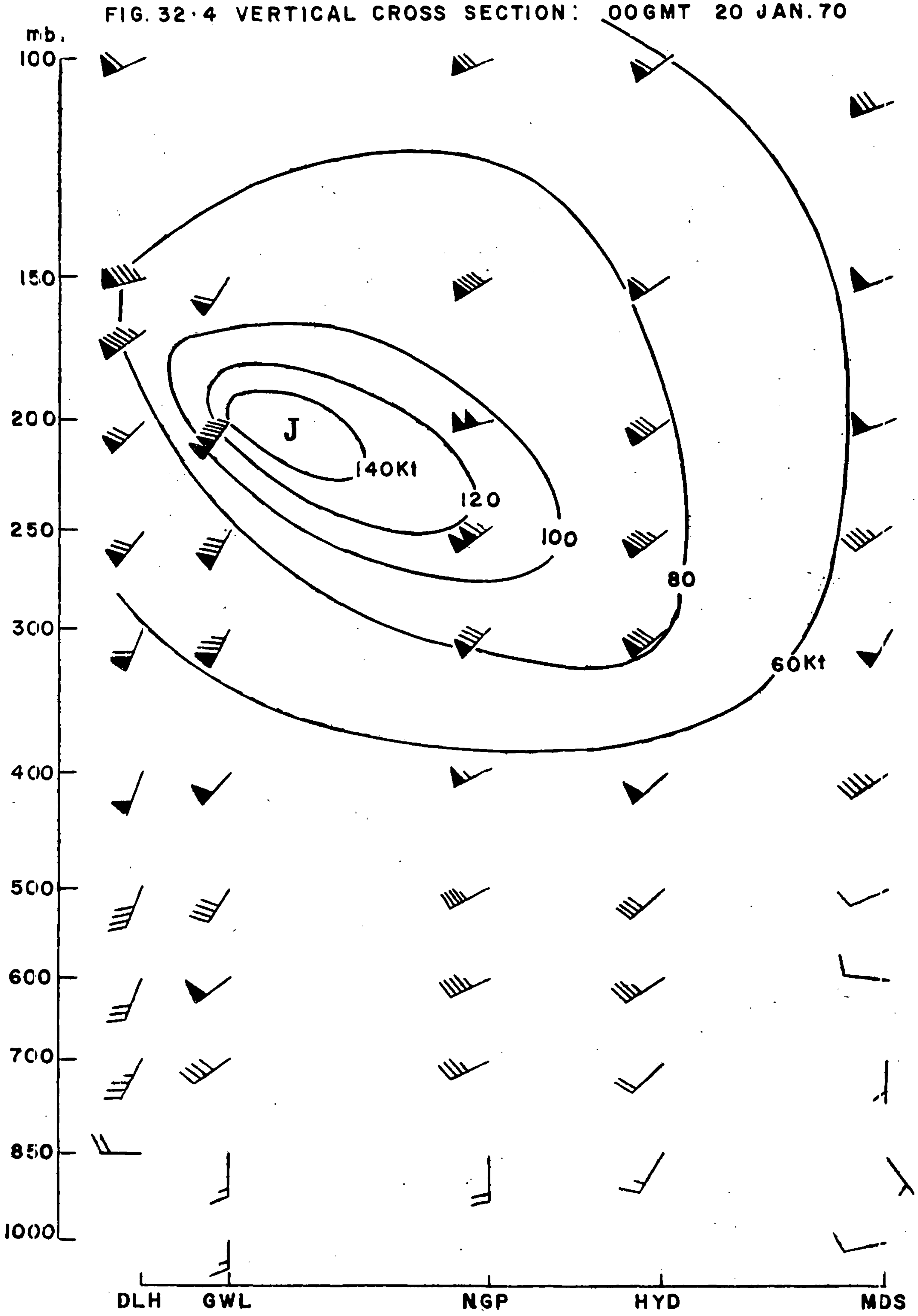
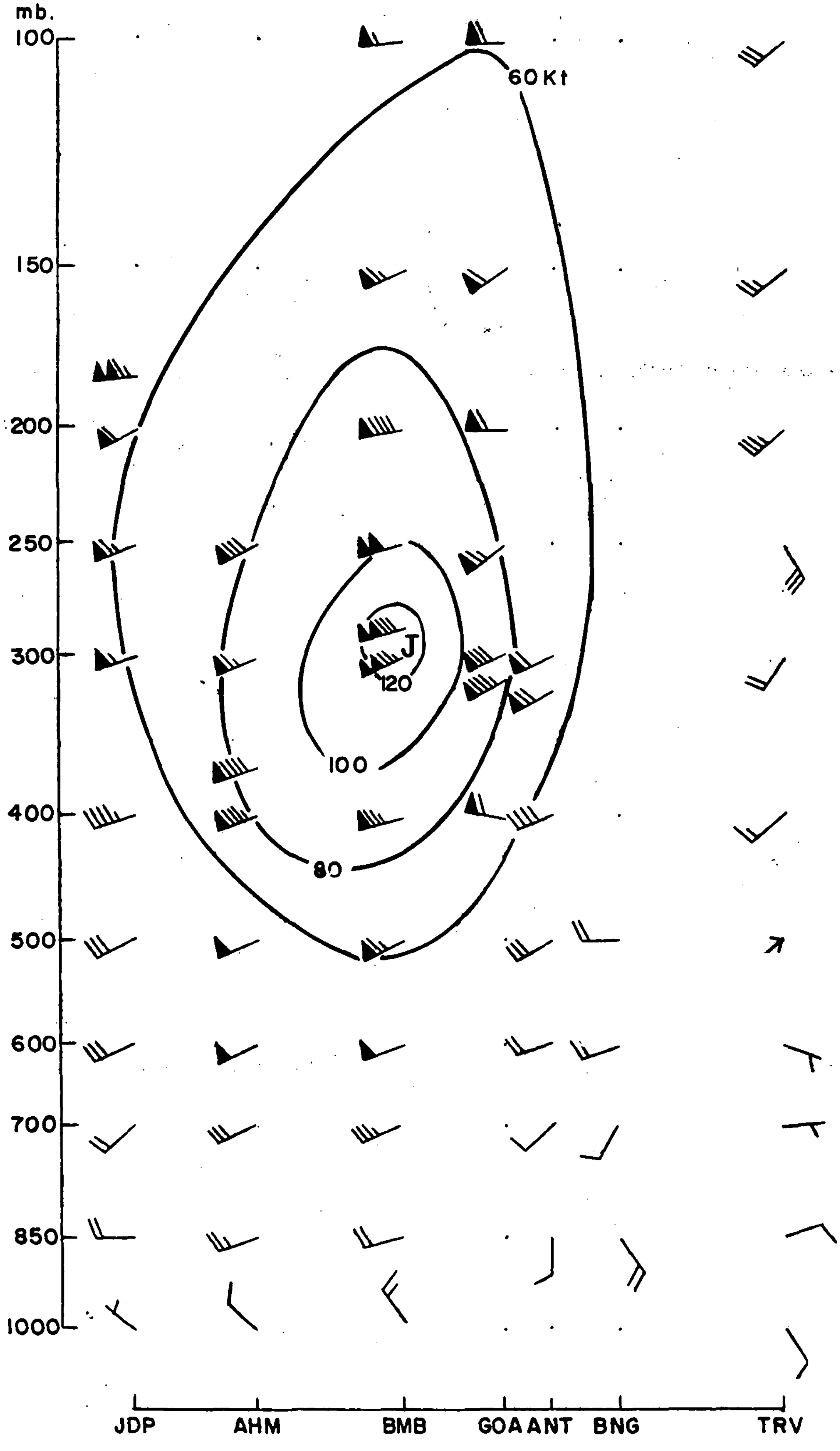


FIG. 32·5 VERTICAL CROSS SECTION : 00 GMT 20 JAN. 70



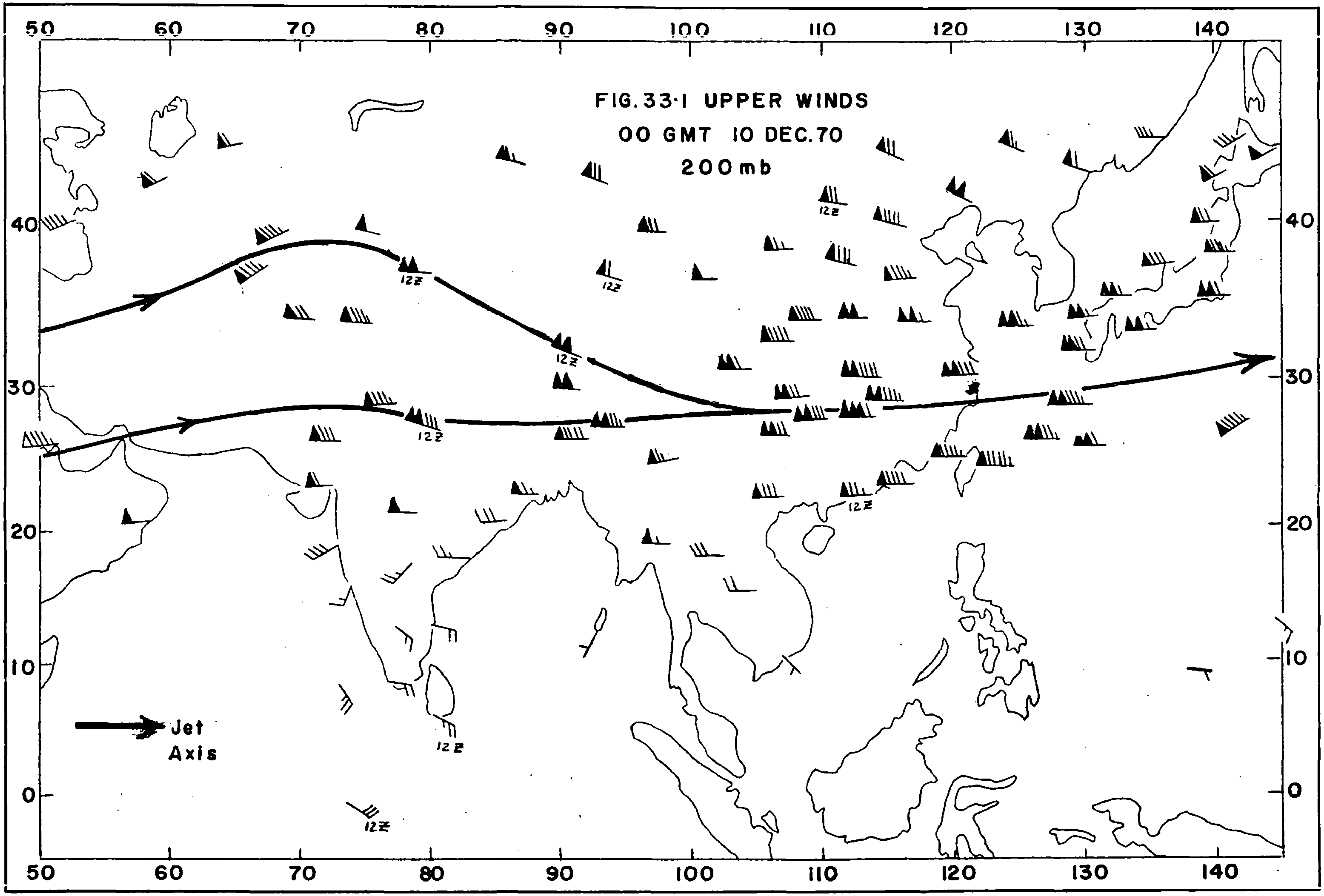


FIG. 33·1 UPPER WINDS
00 GMT 10 DEC. 70
200 mb

FIG. 33·2(a) VERTICAL CROSS SECTION ALONG 77°E: 00 GMT 10 DEC.70

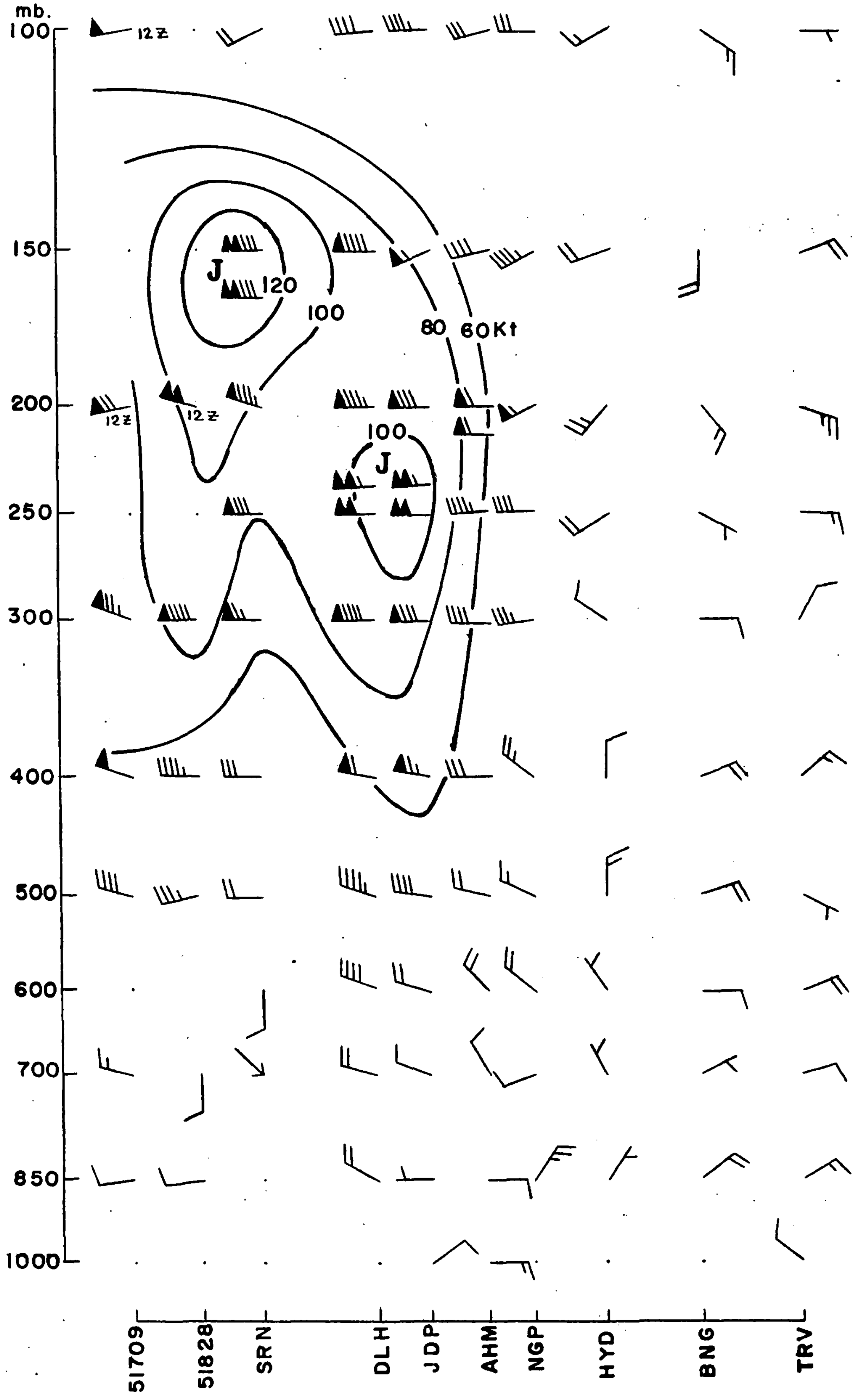


FIG. 33·2(b) VERTICAL CROSS SECTION ALONG LONGITUDE 90°E : 00 GMT 10 DEC.70

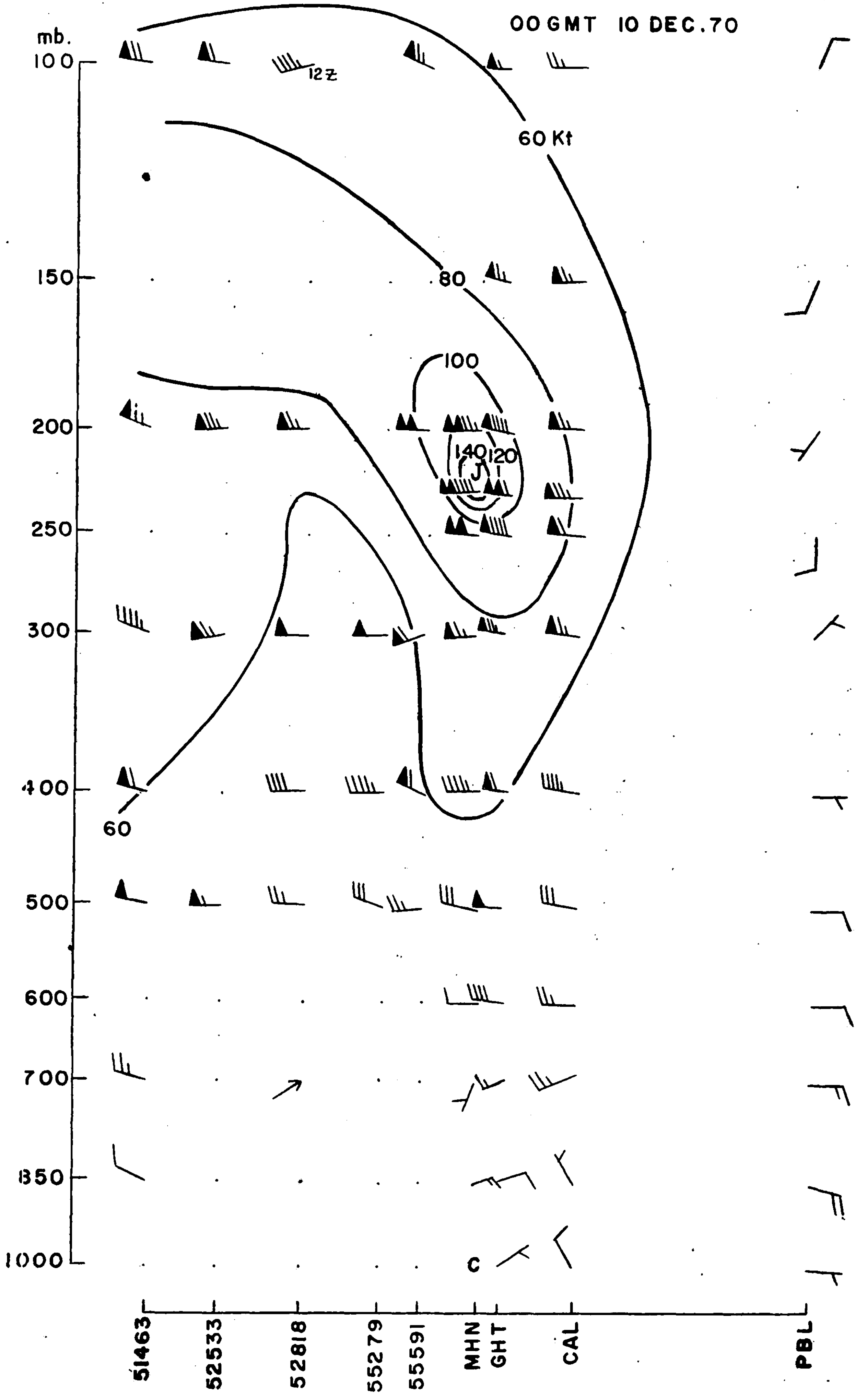


FIG. 33·2 (c) VERTICAL CROSS SECTION ALONG 105°E :
00 GMT 10 DEC. 70

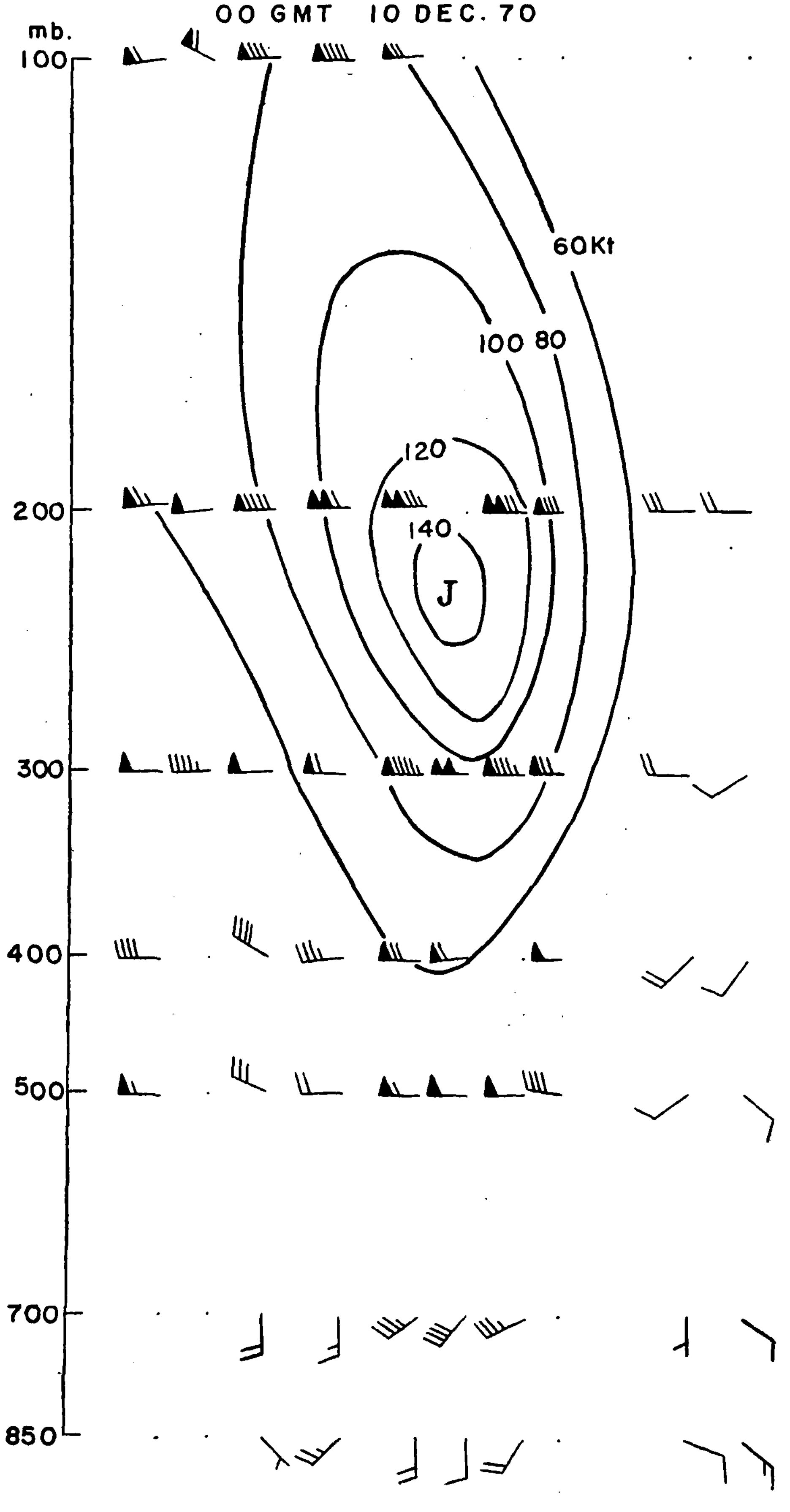


FIG. 33·3 TEMPERATURE PROFILES ALONG LONGITUDE 77°E, 90°E & 105°E : 00 GMT 10 DECEMBER 70

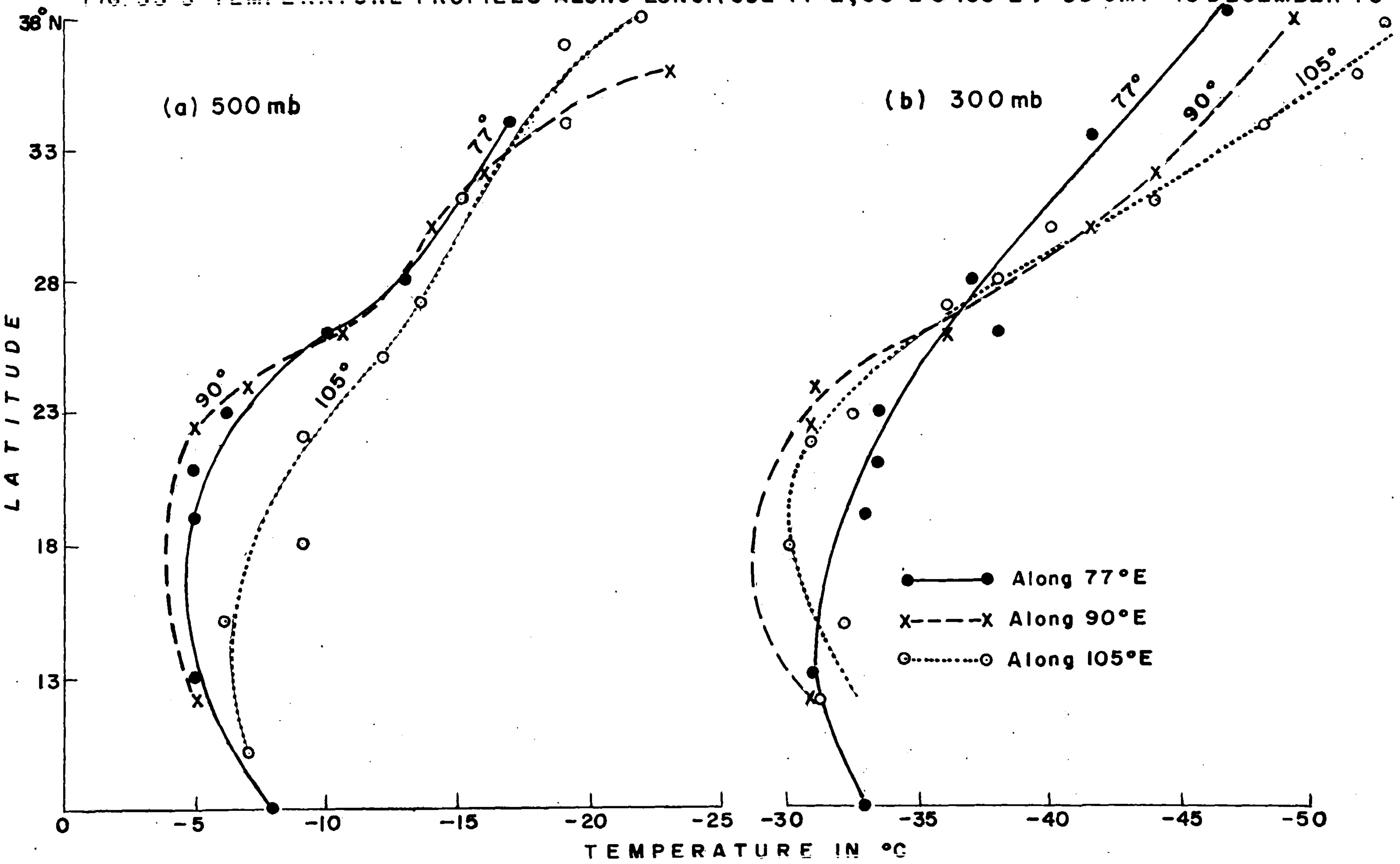


FIG. 34·1 UPPER WINDS 1200 GMT 4 JAN. 70

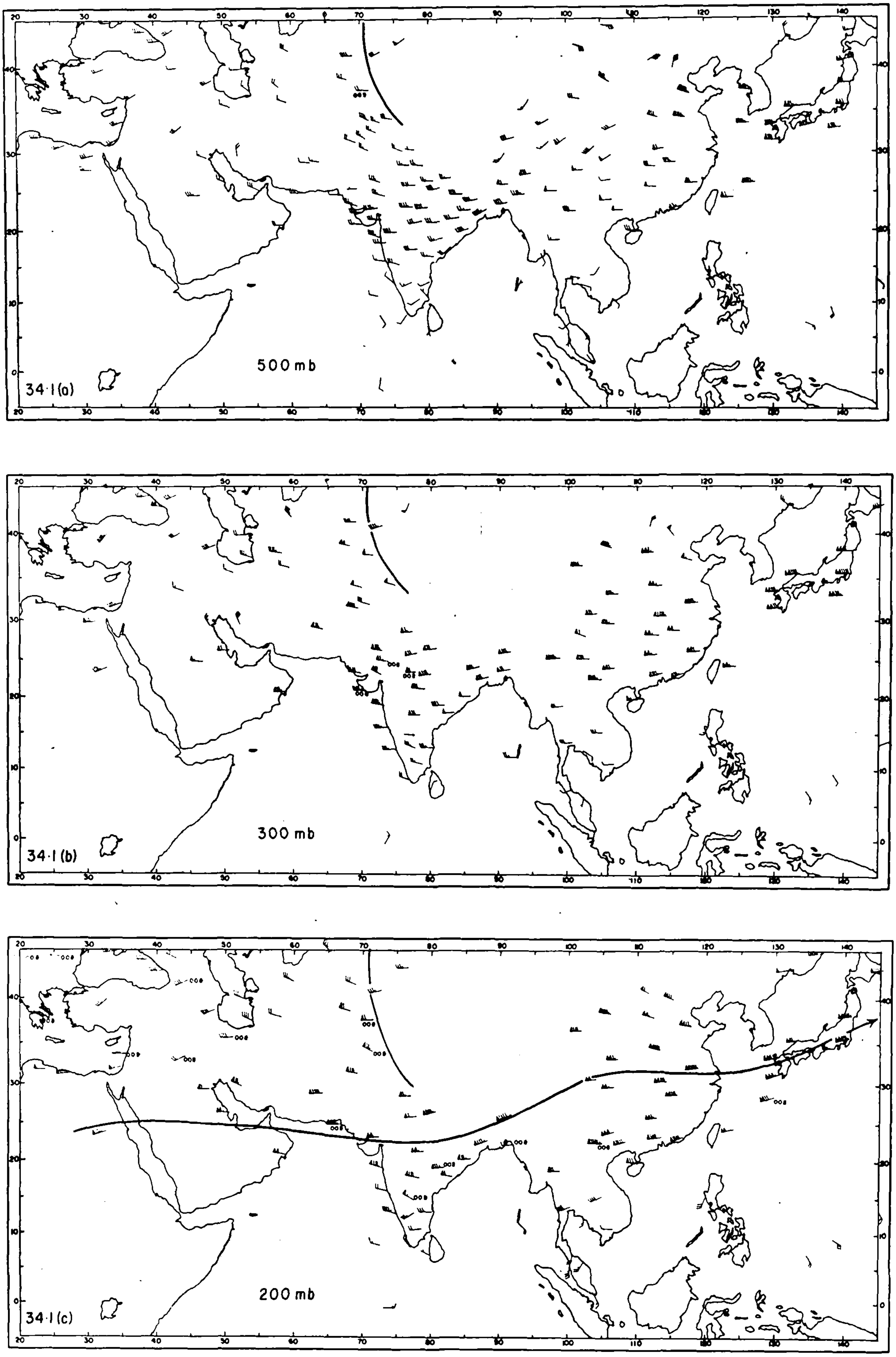
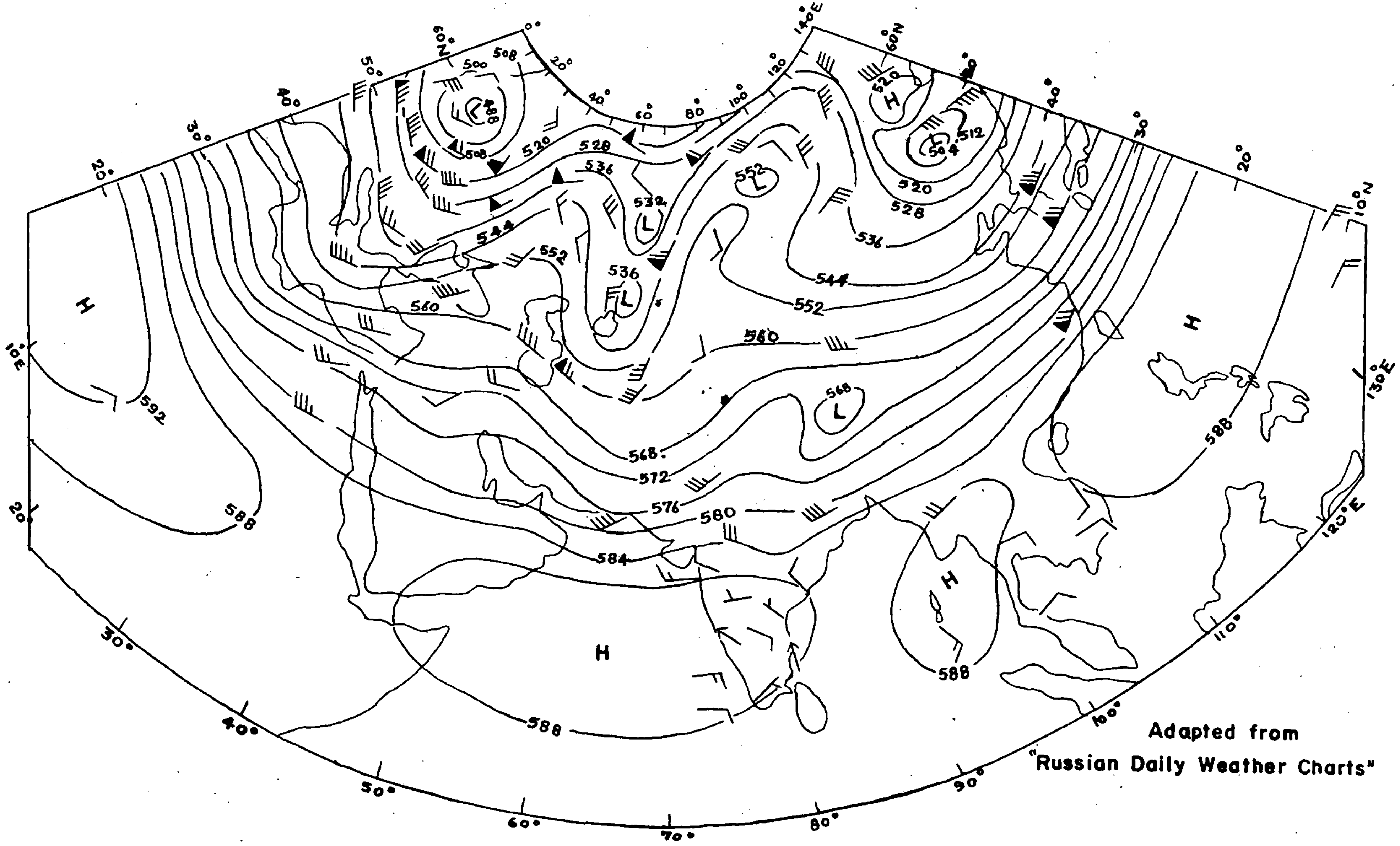


FIG. 34.2 3 JAN. 70 00 GMT 500 mb



Adapted from "Russian Daily Weather Charts"

FIG. 34·3 VERTICAL CROSS SECTION : 12 GMT 4 JAN. 70

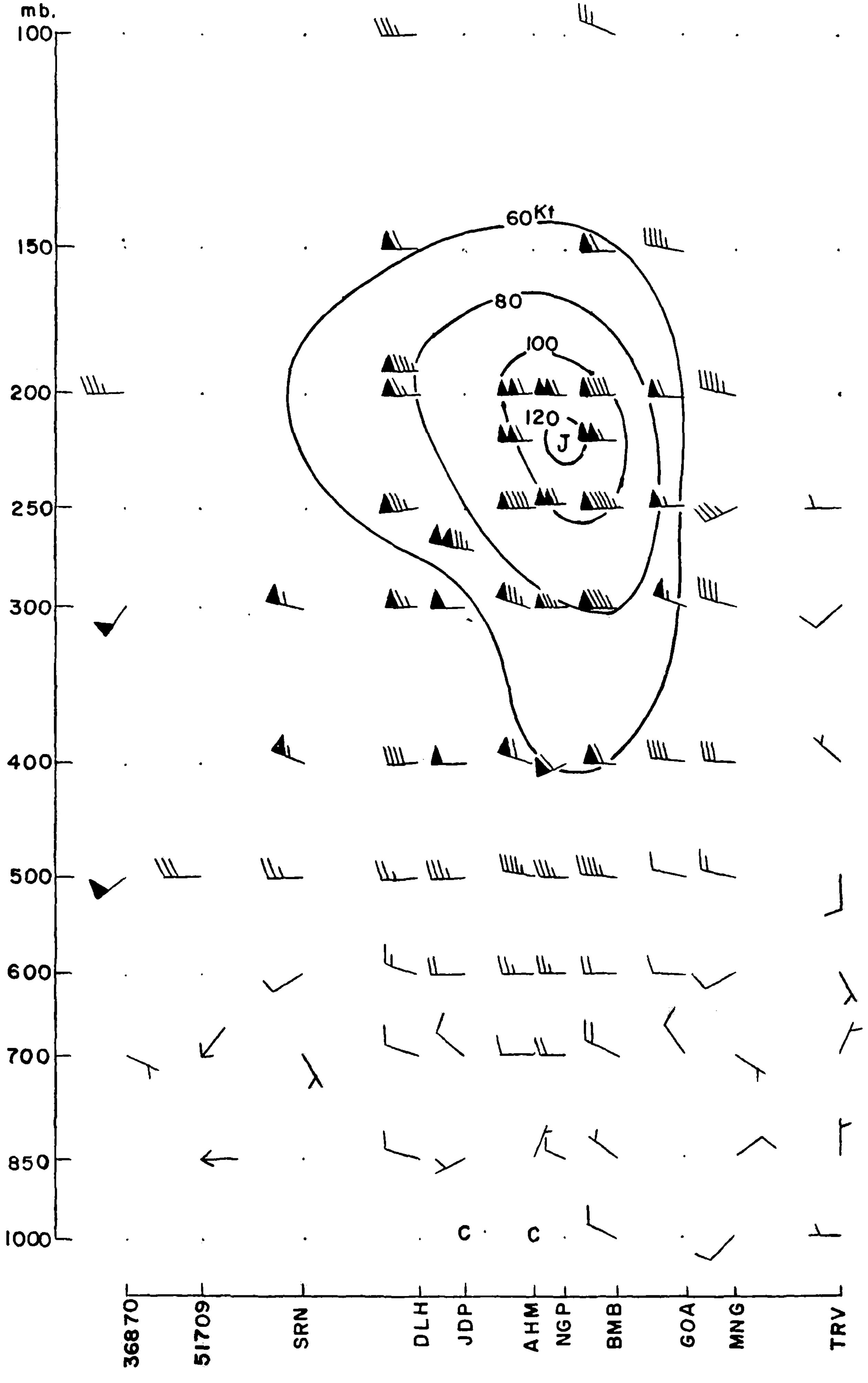
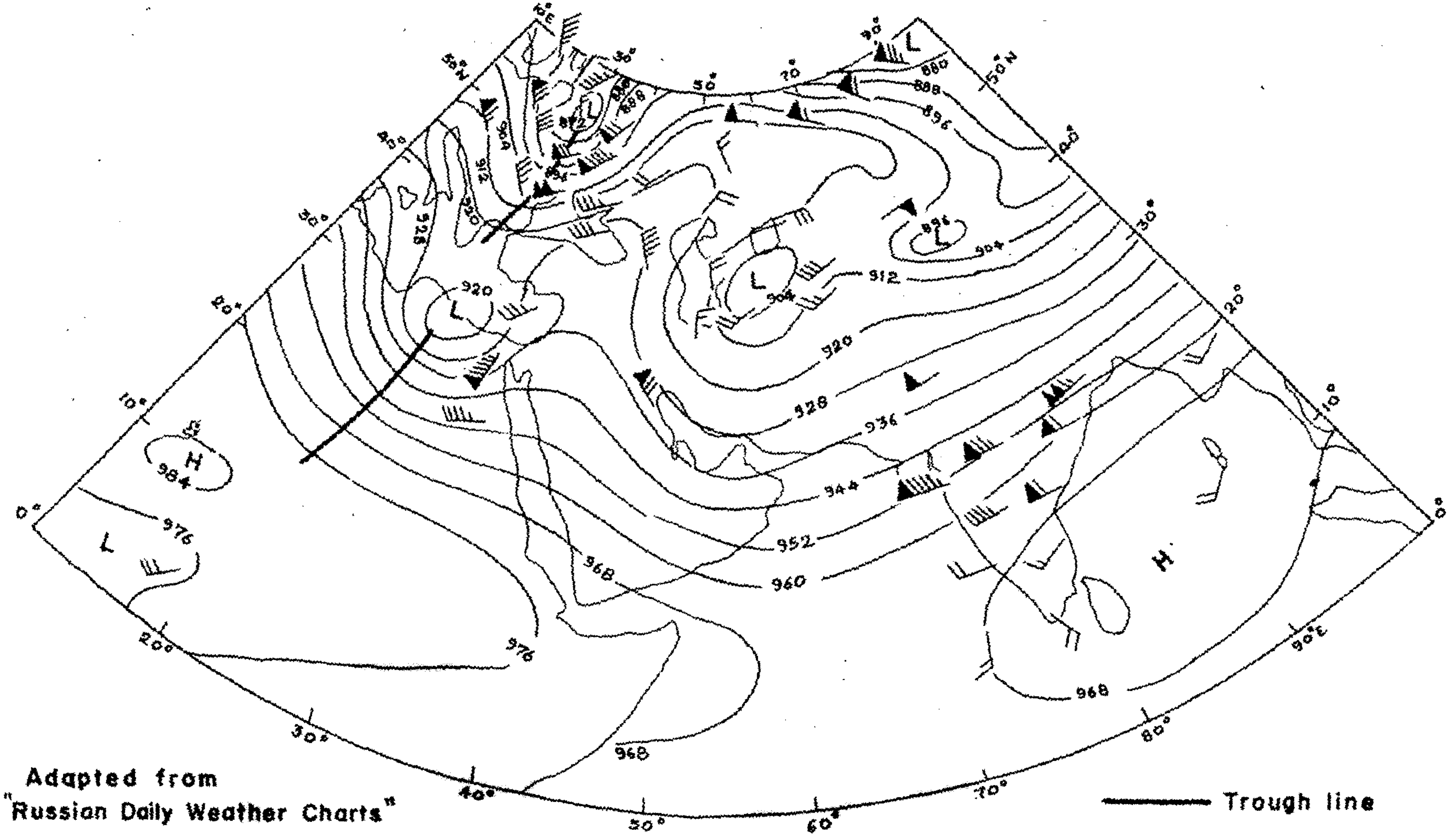
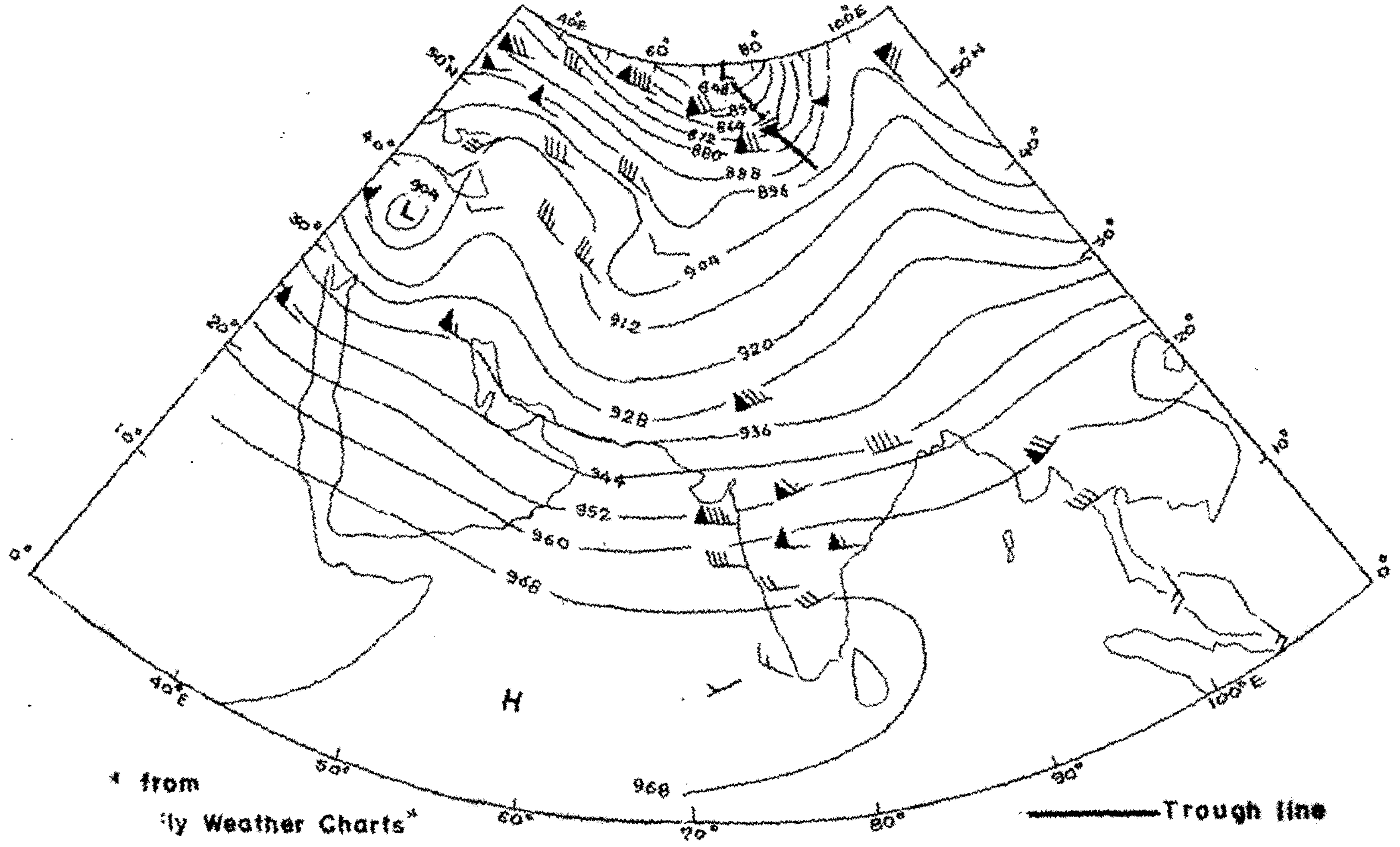


FIG. 35·1 9 JAN. 70 00 GMT 300mb



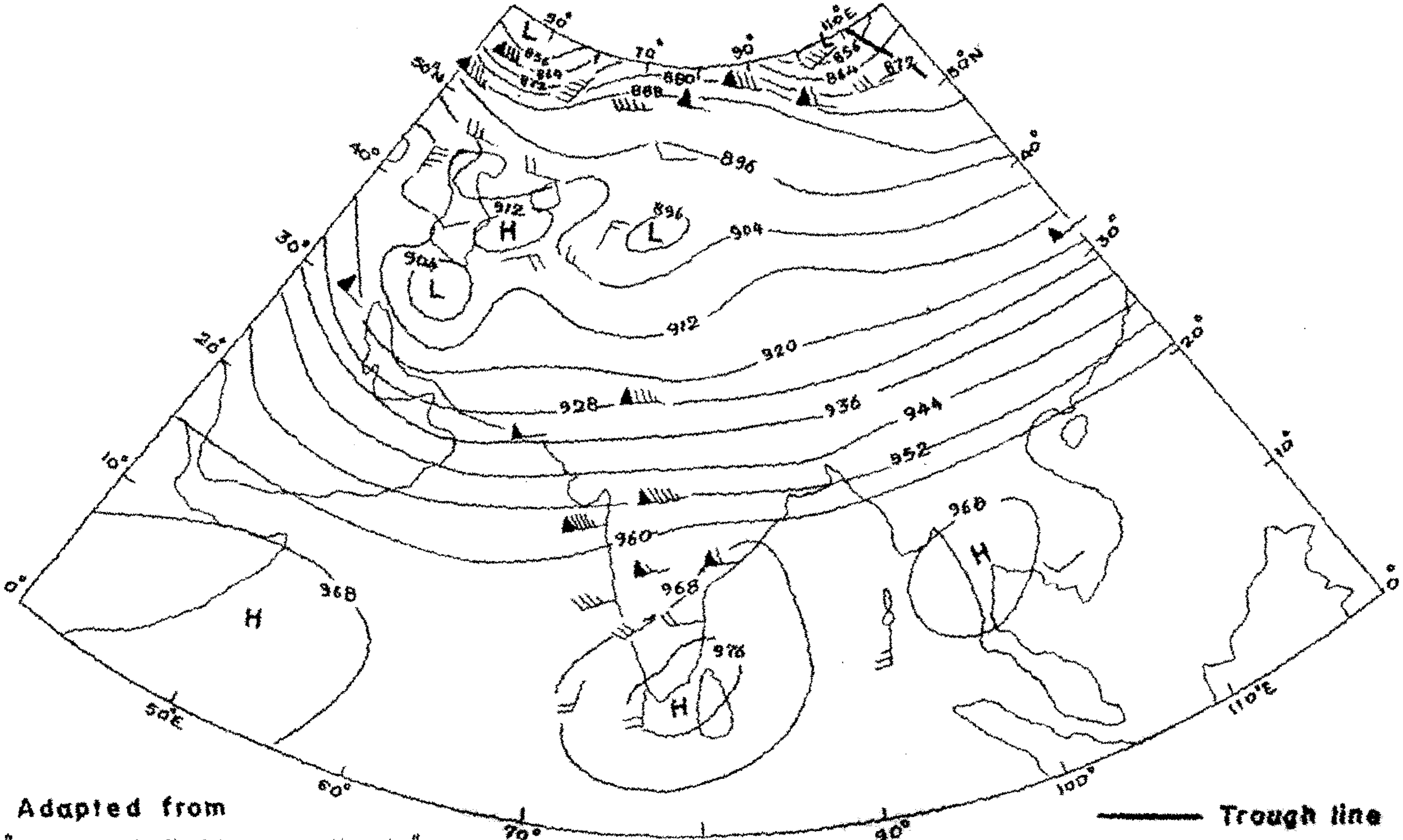
Adapted from
"Russian Daily Weather Charts"

FIG. 35·2 15 JAN. 70 00GMT 300mb



* from
'ly Weather Charts"

FIG. 35·3 17 JAN. 70 00 GMT 300mb



Adapted from
"Russian Daily Weather Charts"

FIG. 35·4 UPPER WINDS 0000 GMT 15 JAN. 70

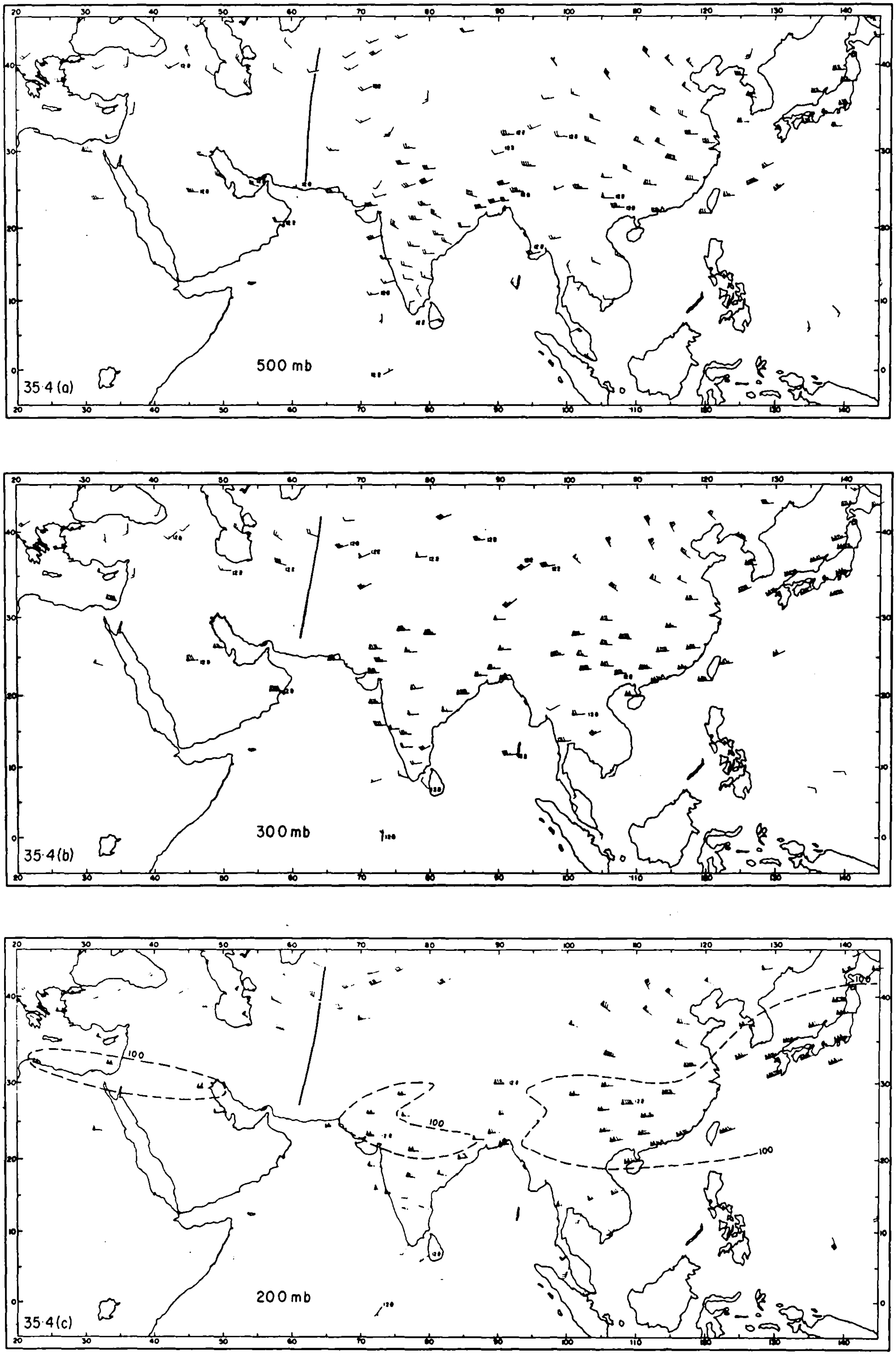


FIG. 35·5 VERTICAL CROSS SECTION: 12 GMT 15 JAN. 70

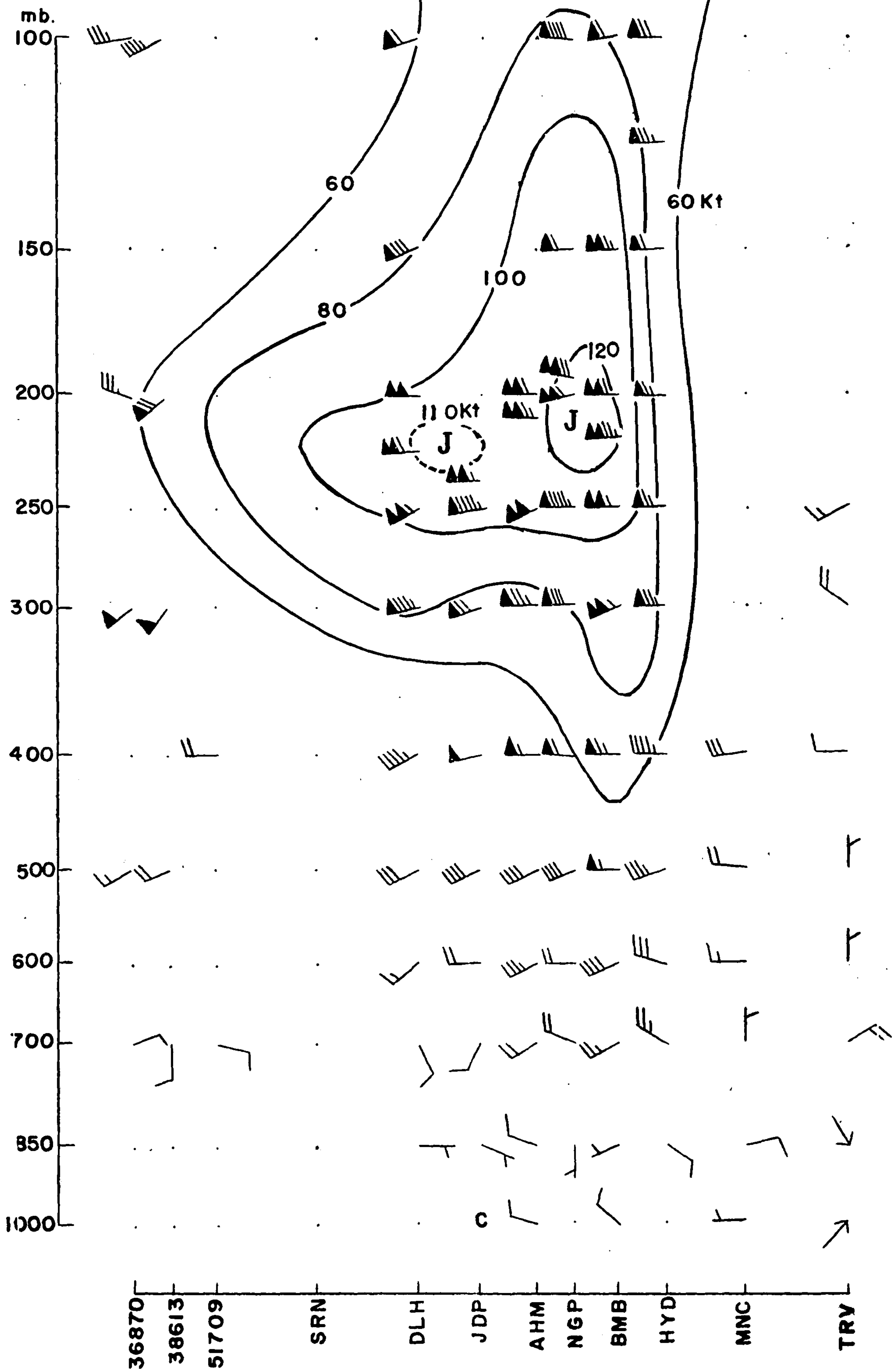


FIG. 35·6

ESSA - 8

15 JAN. 70

ORBIT 4965 (0505 GMT)

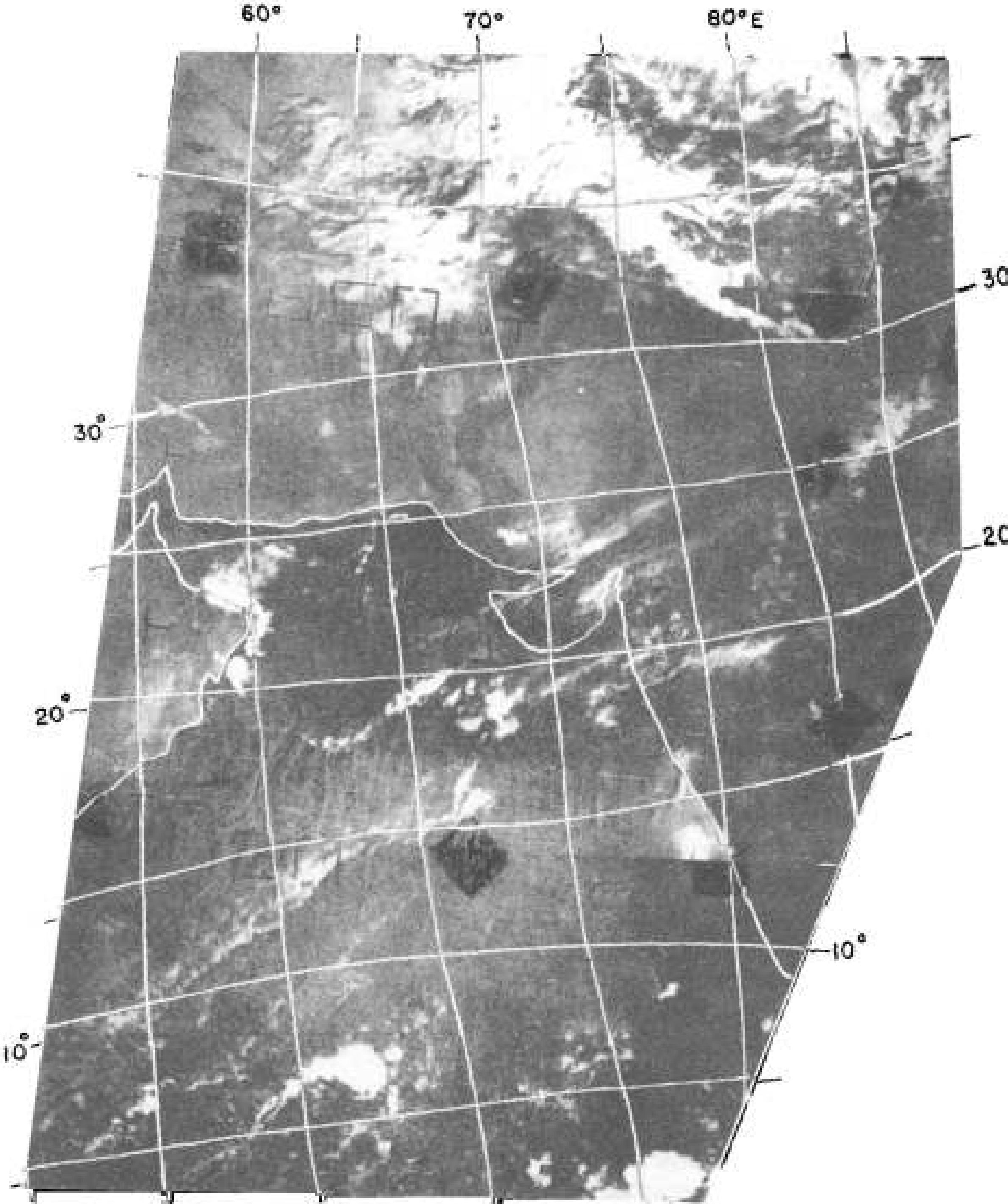
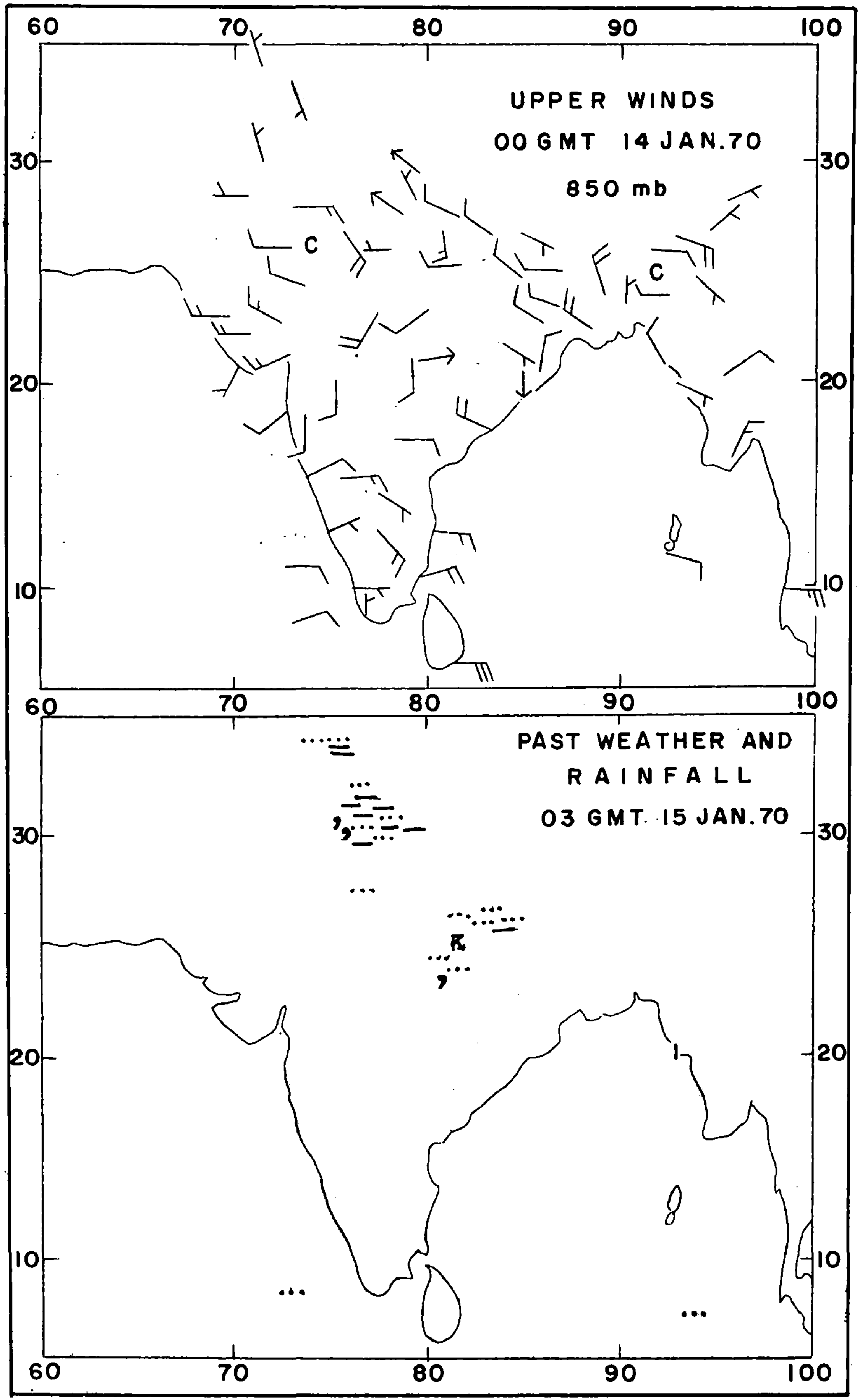
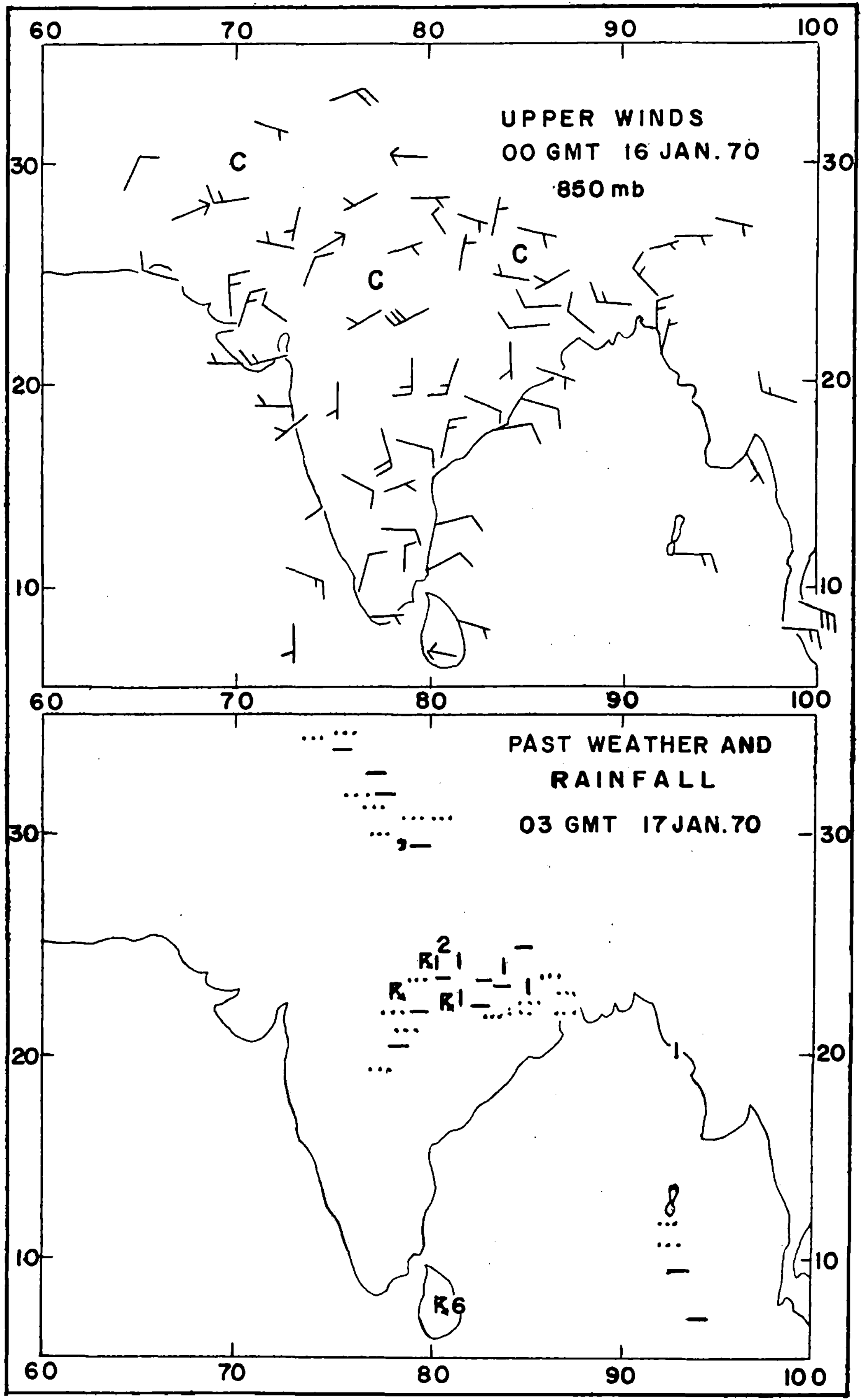


FIG. 35·7



C–Centre of cyclonic circulation

FIG. 35·8



C- Centre of cyclonic circulation

FIG. 36·1 UPPER WINDS 1200 GMT 5 JAN. 71

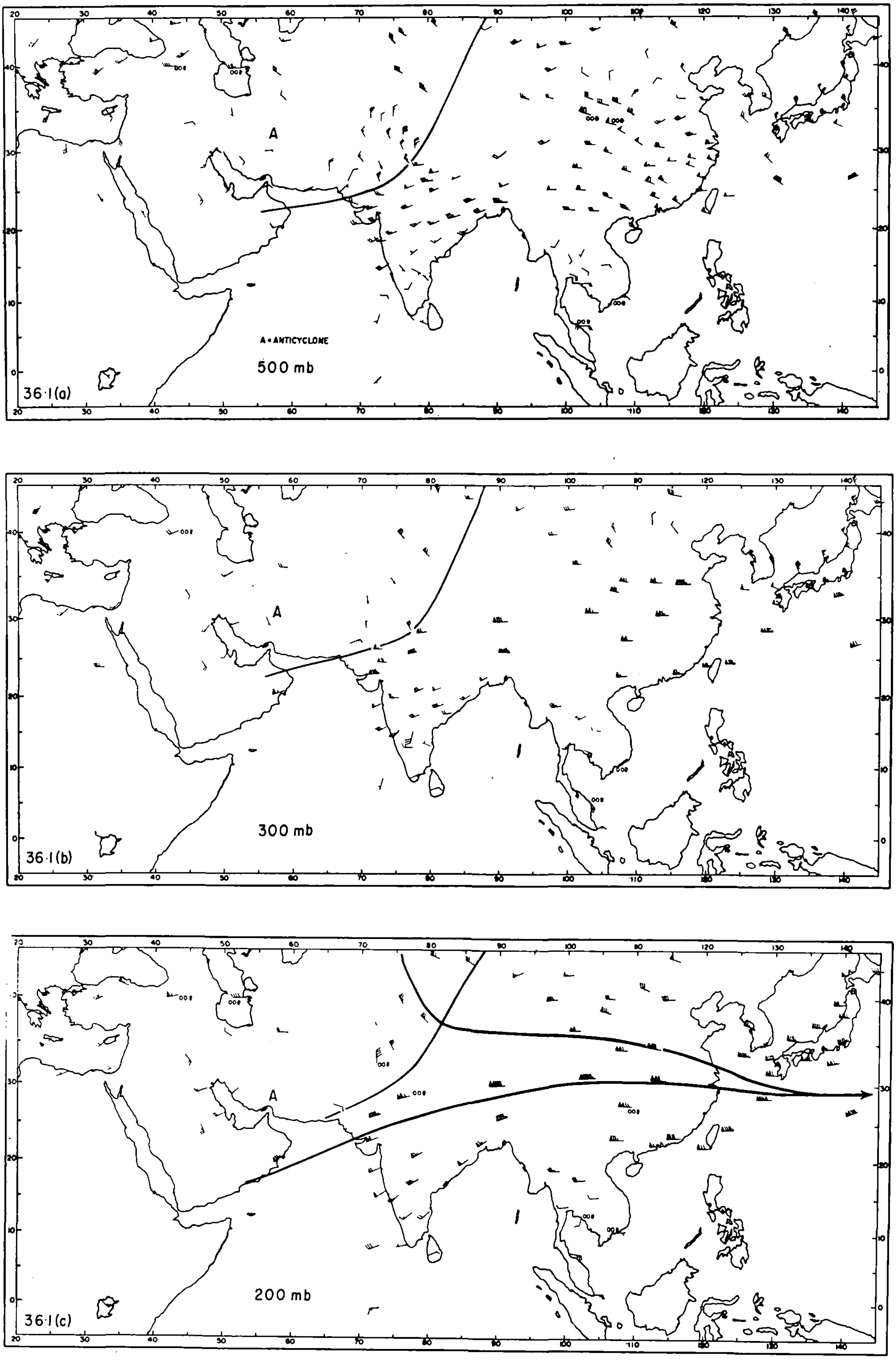
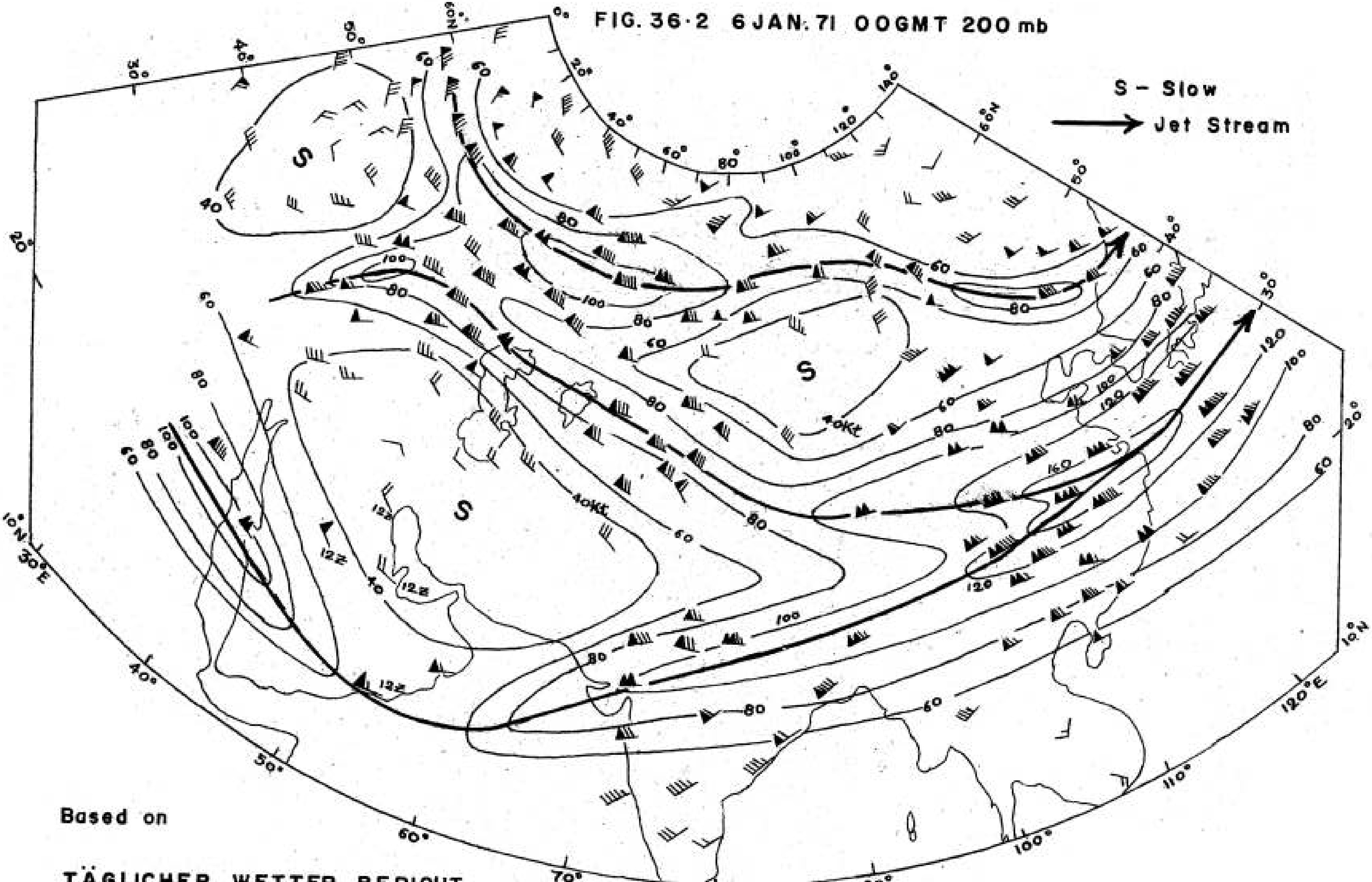


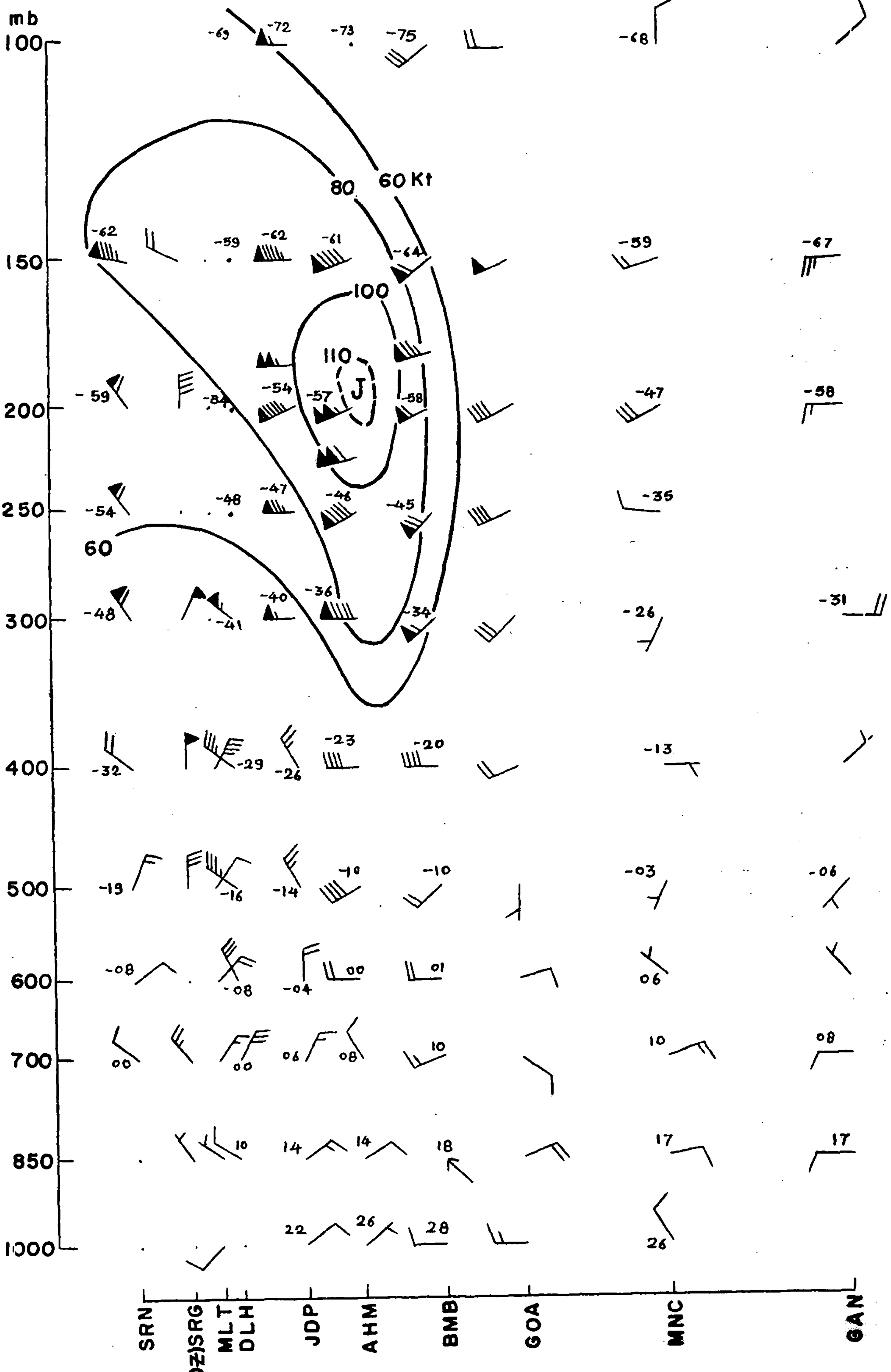
FIG. 36·2 6 JAN. 71 OOGMT 200 mb



Based on

TÄGLICHER WETTER BERICHT
Deutschen Wetterdienstes

FIG. 36·3 VERTICAL CROSS SECTION: 12 GMT 5 JANUARY 71



Plotted figures: TT °C

FIG. 36·4

ESSA 8 DATE : 5 JAN. 71

ORBITS 9422 (0541 Z)

& 9421 (0346 Z)

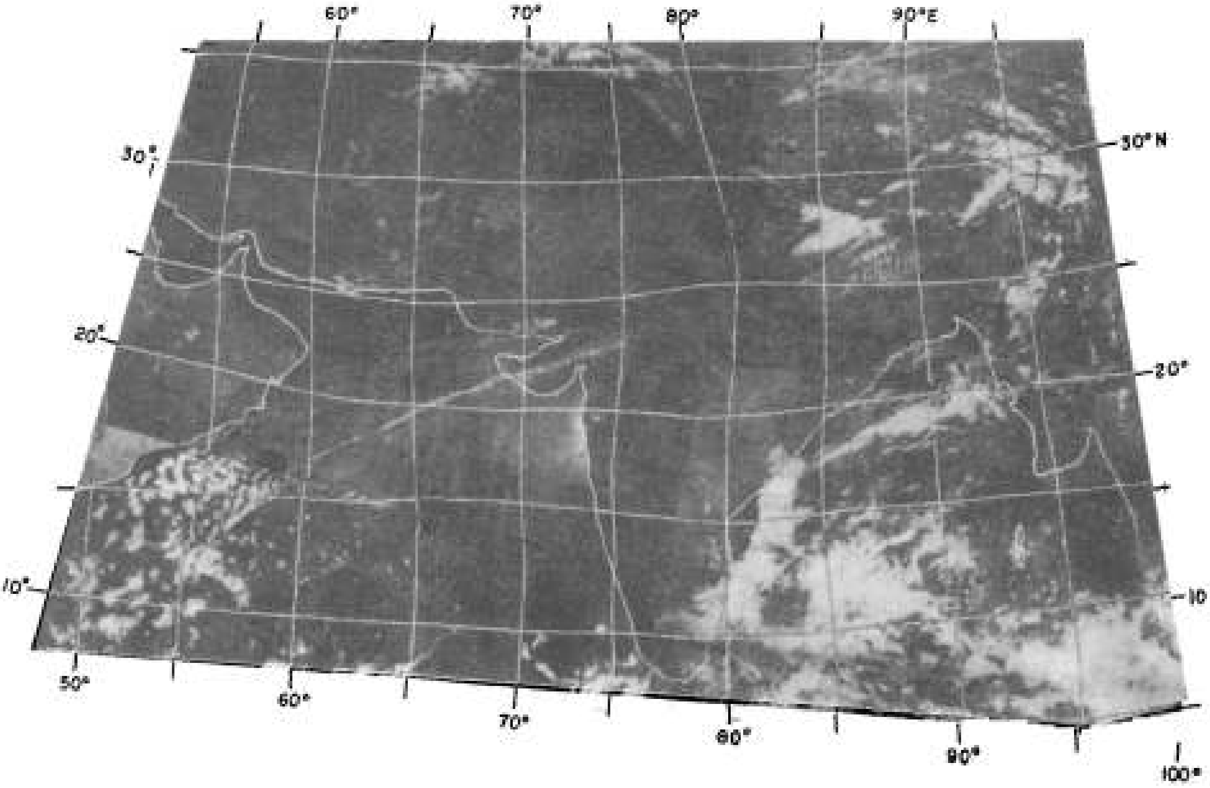


FIG. 37·1 UPPER WINDS 0000 GMT 12 FEB. 71

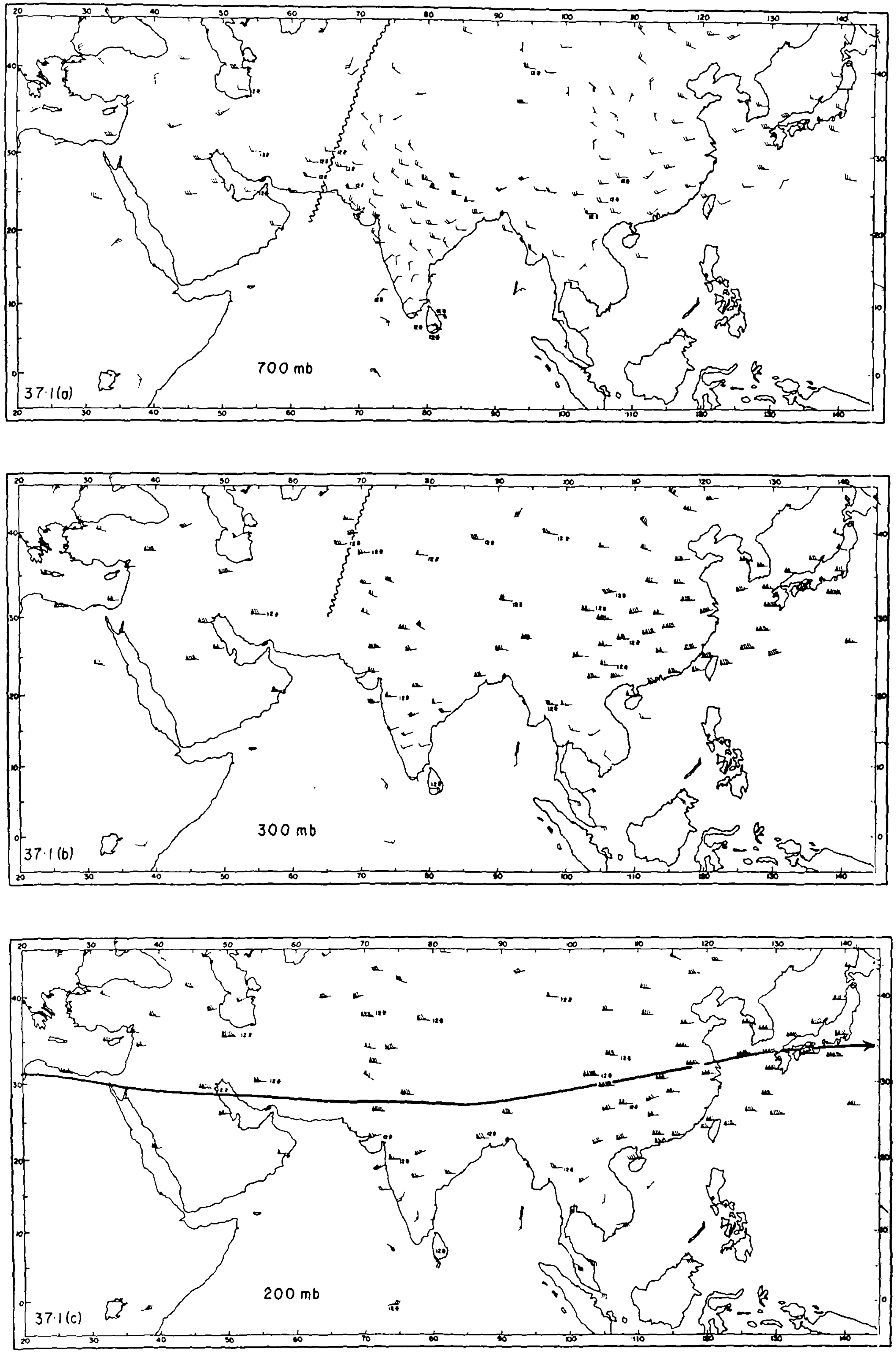
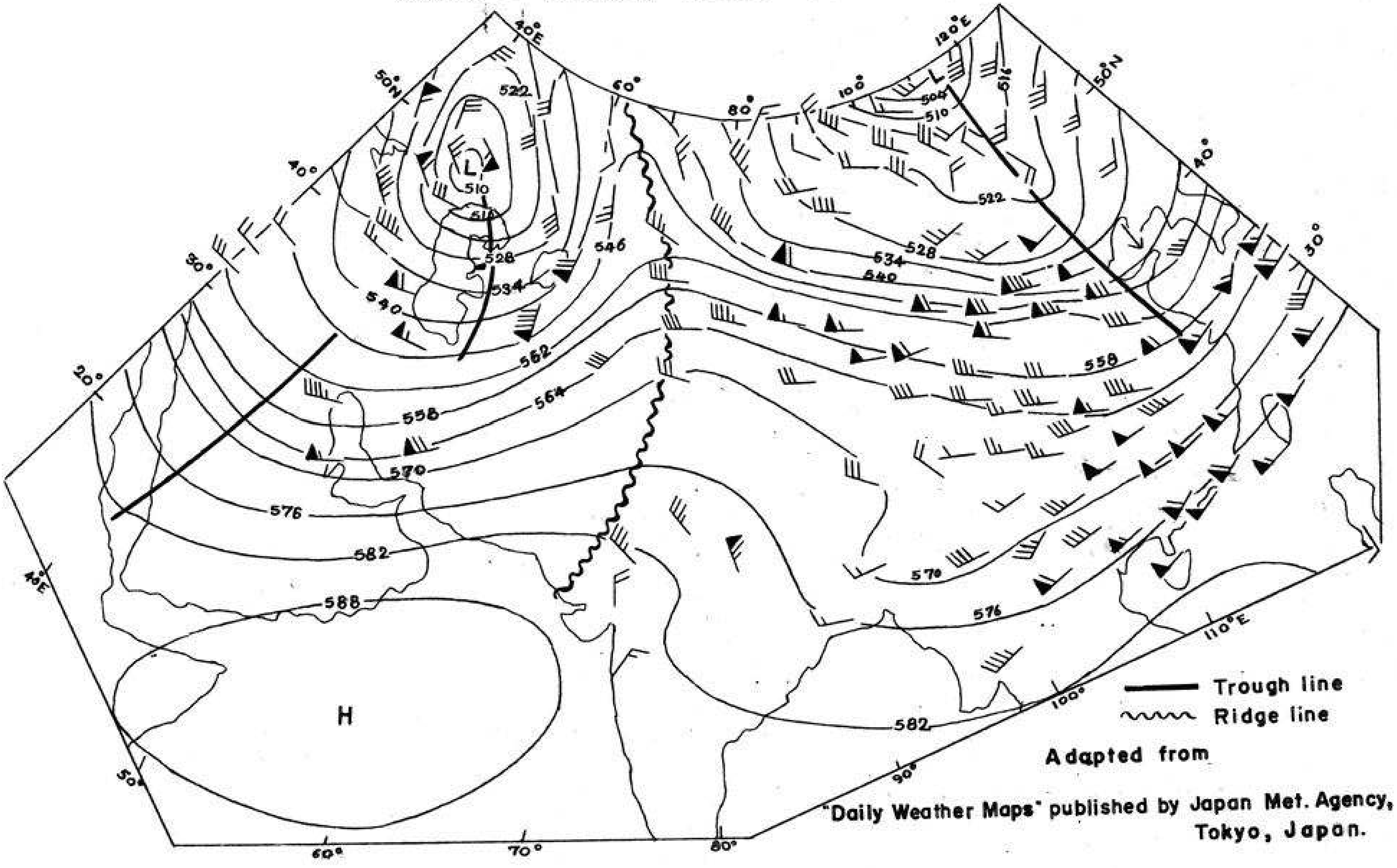


FIG. 3 14 FEB. 71 12 GMT 500 mb.



Adapted from

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

FIG. 37·3 VERTICAL CROSS SECTION : 12 GMT 12 FEB. 71

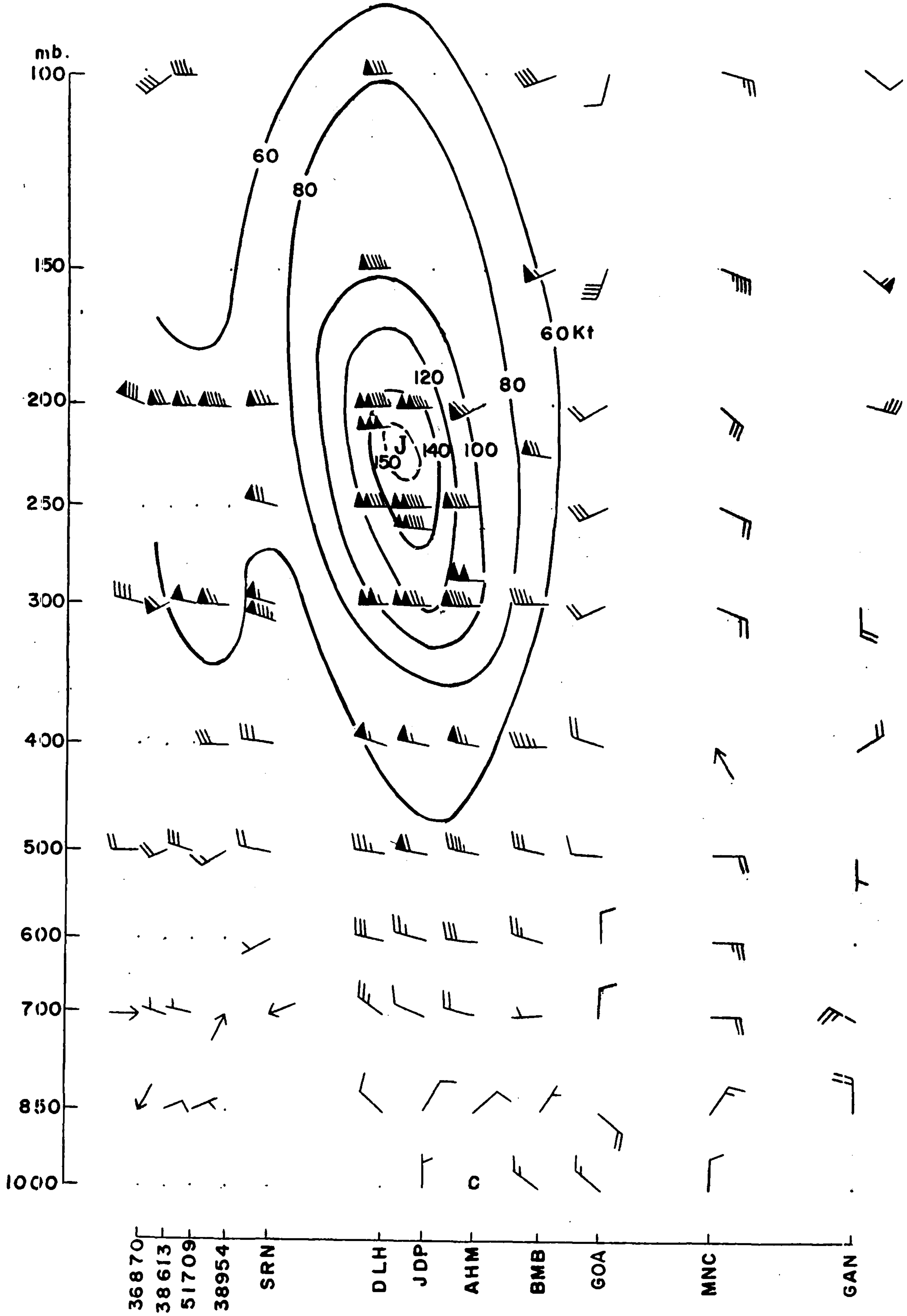


FIG. 37·4 VERTICAL CROSS SECTION : 12 GMT 15 FEB. 71