FMU Rep. No. IV - 6
(OCTOBER 1974)

INDIA METEOROLOGICAL DEPARTMENT

FORECASTING MANUAL

PART IV

COMPREHENSIVE ARTICLES ON SELECTED TOPICS

6. HEAT AND COLD WAVES IN INDIA

BY

V. C. BEDEKAR, M. V. DEKATE AND A.K. BANERJEE

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6. Heat and Cold Waves in India

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Contents:

1. Introduction

1.1 During the period March to July, when the normal temperatures are generally high over the Indian sub-continent, any further rise in the temperature becomes a matter of concern to the people in all walks of life. If the hot spell is prolonged, it creates shortage of water in some areas. For the agriculturist, it leads to a condition for drought. This disastrous phenomenon gives a physiological strain also which sometimes claims heavy toll of livestock and human beings.

1.2 On the other hand, during the period from November to March and sometimes in the month of April, cold dry air blows from a northwesterly/northerly direction and lowers the day and night temperatures. Sometimes, the temperatures go down so much that it leads to a condition of frost, resulting in damage to agriculture.

1.3 There is no fixed periodicity or minimum/maximum extent of spread associated with each hot/cold spell. However, during each hot/cold season, there are 2 to 3 occasions when the hot/cold spells appear and disappear after a few days. This has probably led to the idea of calling them as "Heat/Cold waves".

1.4 By long-standing practice in the India Meteorological Department, a region (or a station) is said to be in the grip of a "moderate heat wave",when the recorded maximum temperatures are above normal by 6°C to 7°C and it will be called a "severe heat wave" if the maximum temperature is 8°C or more above normal.

1.5 Similarly a region (or a station) is said to be in the grip of a "moderate cold wave" when the recorded minimum temperatures are below normal by 6°C to 7°C. If the negative departure reaches or exceeds 8°C, it is said to be under "severe cold wave" conditions.

1.6 Extracts from Technical Circular Forecasting No. 23 dated the 20th December 1958 (brought upto date after incorporating all subsequent amendments) are given below. This gives the ranges of temperatures with the description associated with them.

Extracts from DDGF's Technical Circular Forecasting No. 23*

TEMPERATURES

Magnitude of change or departure in 0°C	Description of change	Description of departure
1 to −1	Little change	Nearly normal
2 to 3	Rise	Above normal
4 to 5	Appreciable rise	Appreciably above normal
6 to 7	Marked rise	Markedly above normal (Moderate heat wave)
8 or more	Large rise	Severe heat wave
−2 to −3	Fall	Below normal
−4 to −5	Appreciable fall	Appreciably below normal
−6 to −7	Marked fall	Markedly below normal (Moderate cold wave)
−8 or more	Large fall	Severe cold wave

Changes may also be described in numerical magnitudes if desired. The use of the word "heat wave" or "cold wave" should generally be restricted to occasions when temperatures are above/below normal by 8°C or more. There is, however, no objection if some prefer to use expressions "moderate heat wave" or "moderate cold wave" when the departures are ±6 or ±7°C respectively. But ordinarily the words "markedly above/below normal" should be used for describing temperature departure of ± 6 or ± 7°C.

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* From DDGF's letter No. W 969 of 22 May, 1971.

1.7 It can be seen from the above definitions that the actual maximum or minimum temperatures do not figure in a direct manner in the description of a heat or cold wave. It is only the departures from normal that define heat or cold wave conditions. Thus, stations in northwest India may record minimum temperatures of the order of 4 to 5°C on a winter day, but technically it may not become a "cold wave" condition. But if the temperatures of the same order are recorded at stations in central India, they may be declared to be in the grip of a cold wave.

1.8 People residing in a place for a sufficiently long time get more or less acclimatized to the normal weather conditions of that place. Human body is quite sensitive to any physiological change which takes place due to significant departure of weather conditions from normal. Perhaps these terms, "heat wave/ cold wave", are designed to take the physiological changes also into account.

1.9 In fact, these terms are used by the United States Weather Bureau to signify a rise or fall of temperature at a given place by at least a specified amount in 24 hours, to at least a specified maximum or minimum. These specified amounts vary with season and locality.

1.10 The characteristic wave aspects like periodicity and frequency are not generally associated with the case of cold or heat wave situations; but these conditions, however, may tend to move in preferred directions, particularly the cold wave.

1.11 For the sake of convenience, this study is split into two parts; the first one deals with heat waves and the second with cold waves.

2. Heat Waves over India

2.1 Climatology

2.1.1 The climatological aspect of heat waves over India has been studied by Raghavan (1966) based on the data from 1911 to 1961. Data for later years from 1962 to 1967 have also been taken into account in the present study.

Table 1 gives the number of severe heat waves which have occurred in the various sub-divisions of India. Table 2 gives the duration of these heat waves for the same sub-divisions.

TABLE - 1

Total number of severe heat waves (based on data 1911 to 1967)

Sub-division	March	April	May	June	July	Total
South Assam	3	15	3			21
West Bengal		1	11	19		31
Bihar Plains		1	7	27		35
Bihar Plateau			5	36		41
Uttar Pradesh, East	7		2	43	9	61
Uttar Pradesh, West	5	2		23	14	44
Punjab	15	2	1	19	11	48
Jammu and Kashmir	16	6	13	18	9	62
Rajasthan, East	2			2	9	13
Rajasthan, West	10	2			2	14
Saurashtra and Kutch	25	7	4			36
Gujarat	3	1	1	1	1	7
Madhya Pradesh, West	2		1	23	8	34
Madhya Pradesh, East	4		3	38	3	48
Orissa	2		3	27		32
Coastal Andhra Pradesh			4	13		17
Vidarbha	1			10	1	12
Telangana				7	1	8
Interior Karnataka, North				5		5
Marathwada				1	1	2
Madhya Maharashtra	1			6	2	9
Rayalaseema			1			1
Konkan	2	1				3
Total	98	38	59	318	71	584
% of Total	17	7	10	54	12	

<u>Note</u>: 1. Sub-divisions given here and in subsequent tables, correspond to those in 1965.
2. Punjab includes Delhi and Himachal Pradesh. West Bengal includes Sub-Himalayan West Bengal.
3. North Assam is excluded from this study.
4. Sub-divisions where the phenomenon was not reported at all are omitted from the Table.

TABLE – 2

Maximum duration (number of days) of severe heat waves (based on data 1911 to 1967)

Sub-division	March	April	May	June	July
South Assam	2	13	4		
West Bengal		1	7	12	
Bihar Plains		1	3	8	
Bihar Plateau			5	10	
Uttar Pradesh, East	3		3	8	9
Uttar Pradesh, West	2	1		8	8
Punjab	7	2	1	7	6
Jammu Kashmir	15	4	9	10	3
Rajasthan, East	6			2	3
Rajasthan, West	7	4			2
Saurashtra-Kutch	6	5	2		
Gujarat	5	2	3	1	1
Madhya Pradesh, West	2		1	6	6
Madhya Pradesh, East	2		1	8	2
Orissa	1		3	6	
Coastal Andhra Pradesh			2	8	
Vidarbha				3	6
Telangana				2	2
Interior Karnataka-North				4	
Marathwada				1	1
Madhya Maharashtra	1			3	1
Rayalaseema			1		
Konkan	1	1			

See Notes under Table 1.

2.1.2 During the hot weather months, March to July, abnormally high surface temperatures occur in certain parts of the country; and this phenomenon progressively spreads from one region to another. There is a systematic variation of the incidence of the severe heat waves from month to month in the country.

2.1.3 As a whole, the occurrence of heat wave is mostly in north India; even there, the interior parts experience more number of heat waves than the coastal areas. The islands are not affected by heat waves. Excluding Jammu and Kashmir, the maximum incidence of severe heat waves has been in East Uttar Pradesh; but there is no region where there is a positive recurrence of severe heat waves every year.

2.1.4 It is seen from Table 1 that there are some preferred localities where heat waves occur; there are also certain regions which have not so far experienced any severe heat wave. The sub-divisions which are not affected by heat waves are (1) Lakshadweep (2) Bay Islands (3) Tamil Nadu (4) Kerala, and (5) Coastal and South Interior Karnataka.

2.2 Frequency

2.2.1 The total number of severe heat waves experienced in each sub-division is given in Table 1. Regions susceptible to severe heat waves have been shown in Fig.1(a) to 1(f) and it is discussed monthwise below.

2.2.2 March – On an average only 17% of the severe heat waves occur in this month. Saurashtra-Kutch is the most vulnerable region. Fig. 1(b) shows that there are two regions which are free from heat waves during this month i.e.

i) Bihar and West Bengal and

ii) north Interior Karnataka, Andhra Pradesh and Marathwada.

2.2.3 April – As the sun moves up the northern latitudes during this month, one would naturally expect that this month will have greater frequency of heat waves than the previous one. But this is not so. The frequency of occurrence sharply falls to 7%. Moreover, many areas like Madhya Pradesh, East Uttar Pradesh, Orissa, Madhya Maharashtra and Vidarbha (and even East Rajasthan) have not recorded any heat wave even though they have heat waves in March. Fig.1(c) shows that there are two distinct belts where heat waves occur – one in the western sector from Jammu-Kashmir to Konkan and another over Bihar Plains, West Bengal and South Assam.

2.2.4 May – In this month, Jammu Kashmir is the most susceptible region. The frequency of heat waves over the country slightly increases (to 10%) and in general there is a shift in their activity from western region to eastern parts of the country; but it is seen from the Fig.1(d) that West Uttar Pradesh and Rajasthan are free from severe heat waves.

2.2.5 June – Nearly 54% of the total number of incidence in the whole year are recorded in this month alone. In particular, East Uttar Pradesh experiences the maximum number of severe heat waves. In 56 years, it has recorded 43 severe heat waves in this month alone out of a total of 61. Next comes East Madhya Pradesh which has recorded 38 severe heat waves out of a total of 48.

It is interesting to note from Table 1 that Rajasthan which is one of the hottest parts of India has hardly recorded any heat wave; another interesting feature is that the west coast from Kutch-Saurashtra to Kerala is free from severe heat waves (Fig.1(e).

During the first half of this month, there is a tendency for more occasions of heat waves to occur in North Interior Karnataka and Madhya Maharashtra; in the second half of the month a similar tendency is noticed in the area comprising of Uttar Pradesh, Punjab and West Madhya Pradesh.

2.2.6 July – In this month the incidence of the waves as a whole is much less – only 12%. The peninsular India becomes almost free from the occurrence of severe heat waves (Fig. 1 f). There is a maximum tendency for the incidence of these waves in the areas of West Uttar Pradesh and Punjab.

2.3 Intensity

2.3.1 As the measure of the intensity of a heat wave is the departure of maximum temperature from its normal which is always different for different days and stations, the highest temperature is usually, though not necessarily, reached during the most intense wave.

2.3.2 Raghavan (1966) has presented a map based on the data from 1881 to 1964 (Fig. 2) which holds good today also; in this figure, the highest maximum temperatures ever recorded are depicted by isotherms. It is seen from data available that Alwar (in East Rajasthan) holds the record for highest temperature of 50.6°C or 123°F (on 10th May 1956).

2.3.3 Normally in the severe heat waves in India the departure from normal is about 8° to 9°C; however maximum temperatures 9° to 10°C above normal have often been recorded in East Uttar Pradesh and Bihar Plateau. During the month of April, this much intensity is not unusual in Assam.

2.4 Persistency

2.4.1 As far as the persistency of these waves is concerned, their duration over the country is generally about 5 to 6 days. The maximum period of a wave in the country was 15 days in March 1921, and this wave was mostly confined to Jammu-Kashmir. In the plains, there was a wave which persisted for 12 days, (20th June to 1st July 1926). Obviously if a wave persists for a long period, it may turn out to be quite intense also. The maximum duration (number of days) of severe heat waves is shown in Table 2, sub-divisionwise.

2.4.2 Generally a severe heat wave does not last for more than a day or two in a sub-division but in Bihar Plateau it may persist for as much as 4 to 5 days.

There is a tendency for these severe waves to persist longer in the month of June than in the other months, in the areas of West Bengal, Bihar Plains, East Madhya Pradesh, Uttar Pradesh and Punjab.

2.5 Extent of coverage

2.5.1 The areal coverage at a time by the severe heat waves varies from wave to wave, from a portion of a sub-division to a whole sub-division. As the season advances towards the end of June, the tendency of these waves is to cover larger areas. In July, these waves do not extend beyond an area of 3,00,000 to 4,00,000 sq. km. The largest area coverage on a single day - so far on record - in the country was associated with the wave of 26th June 1926 (Fig.3), total area coverage being about 8,00,000 sq. km.

2.6 Movement of heat waves

2.6.1 Generally heat waves develop in the northwestern parts of India or the northern parts of Pakistan. From these areas, these waves expand to the neighbouring sub-divisions of the country. Heat wave may also develop in situ over any region. It is not unusual that on some occasions, two heat waves develop at the same time, over different regions of the country.

2.6.2 It is noticed that Punjab and Saurashtra and Kutch sub-divisions are the most favourable areas for development of these waves. In particular, these develop near Ambala or Veraval and then expand from that area to cover larger area. When they cross Long. 78°E, they very rarely survive.

2.6.3 Finally when they shrink, the shrinkage may take place from one or more directions or from all the sides, with or without losing their intensity. Sometimes, waves suddenly disappear because of cloudy weather with (or even without) precipitation associated with fast advancing western disturbances etc.

2.6.4 Probably because the mean winds are northwesterly over the country north of Lat. 20°N, these waves move or expand eastwards or southwards but they never move westwards. If these waves move southward, they die and shrink rapidly. The waves which form in Jammu and Kashmir and Assam sub-divisions, die in the same regions without movement.

2.7 Factors favouring heat wave

2.7.1 It is mentioned earlier that heat waves occur during the months of March to July. It is, therefore, essential to see the normal circulation patterns on the synoptic charts for surface and upper air for these months.

2.8 Normal winds

2.8.1 With the progressive northward march of the sun, the equatorial trough rapidly shifts northward from its winter location on the surface chart. By April and May it becomes the dominant feature over the Indian sub-continent. There are two anticyclones, one situated over the Arabian Sea and the other over the Bay of Bengal, which give an anticyclonic flow over both the coasts and adjoining parts. Along the northern latitudes of the country there is northwesterly to westerly flow.

2.8.2 At 1.5 km asl in March-April the anticyclone over Arabian Sea sometimes spreads as far as the east coast of the country giving northerly or northeasterly winds over the West Bay of Bengal and the anticyclone of the Bay of Bengal becomes a part of the anticyclone over Indo-China and Cambodia. It gives a col region in the East Bay of Bengal; ~~With~~ with the result, the flow of streamlines in the northern latitudes becomes westnorthwesterly to westerly.

2.8.3 But at 3 km asl an anticyclone lies over the north Peninsula. It maintains the westerly flow in the north, and northeasterly flow in the southern parts. At 6 km asl the anticyclone moves towards the south resulting in strong westerly flow to the north of 15°N.

2.8.4 As the season advances, in May, these two anticyclones over the sea areas disappear which gives a zonal flow with a feeble trough in the eastern half of the Peninsula. There is a tilt in the trough and it runs in a north-northeasterly to southsouthwesterly direction in the lower levels. At 6 km asl a ridge lies over north Peninsula resulting in westerly/northwesterly flow to the north of 20°N and northeasterly flow in the southern Peninsula.

2.9 Weather

2.9.1 Considering the upper air features mentioned above, it can be seen that there is a continued flow, throughout the season, of dry continental air, which gives clear weather north of 20°N. The same is occasionally disturbed by the western disturbances moving across north India, as a trough or closed cyclonic circulation. As there is no possibility of any moisture incursion into northwest India, it remains practically hot and with the clear skies which provide maximum insolation. The warmer dry air is then transported to the east and southeast of that region as per the flow pattern.

2.9.2 The above facts can be utilised in predicting the heat waves. Some work, mostly in the sub-tropical regions where the air masses are distinct, is available. Considerable amount of work has been done on these lines in the United States of America, but no direct method to predict the severe heat waves, leave alone their intensity, movement and extent, is so far codified. Still the problem remains to be solved. McQueen and Cadesman Pope (1957) have shown the correlation of the heat waves with the thickness of air mass between 1000 mb and 500 mb levels. It gives an advance indication of the approach and decay of these waves.

2.9.3 On similar lines, an attempt has been made to see whether there is any correlation between the thickness of the layer 1000-500 mb to the severe heat waves in India. It has been dealt with in detail in Appendix I. Many analysed charts have been presented to show that in India also the thickness of the layer 1000 mb-500 mb has a distinct correlation with the heat waves. It gives a prior indication of its development and decay.

2.10 Method

2.10.1 The ridges and troughs in the upper air flow and their amplitudes which bring about a dynamic succession of pressure systems on the surface chart are of prime importance in producing these waves at the surface. Therefore, any positive difference in a 4-day or a longer period in 500 mb height changes and 1000-500 mb thickness changes will unmistakably define the ridge as possessing warm characteristic. It will be noted that the thickness changes comprise the greater portion of the 500 mb height rises, indicating that at sea level the pressure increase will be only nominal. This fact can easily be observed by substracting the 1000-500 mb thickness values from 500 mb height values to obtain the 1000 mb height changes.

2.10.2 The resultant 1000 mb chart would also show the development of a trough or a ridge in the initial stages. It will decide the air flow; and if it is flowing from the source region of high temperature, it will transport this warm air to the concerned region.

2.11 Conclusion

2.11.1 The above mentioned factor, i.e. the thickness should be above normal, is one of the major factors which is indicative of severe heat waves. Though a number of factors are essential to produce the ideal conditions for the formation for these waves, it is not ruled out that even some of them will also be able to develop them; but then it may not be a severe one or of long duration. These favourable factors are listed below in brief to be considered as parameters; but the list is not exhaustive. There may be some unexplored ones.

2.11.2 The favourable factors are - (a) hot dry air should prevail over the concerned region (b) there should be a region of warmer dry air and an appropriate flow pattern for transporting the air over the region (c) there should be little or no moisture present in the upper air over the area (d) sky should be practically cloudless to allow maximum insolation over the region

(e) the lapse rate should approach dry adiabatic in the air mass to allow warming to a considerable depth (f) finally there should be a large amplitude anticyclonic flow or the thickness values should be considerably above normal in all layers.

3. Cold Waves over India

3.1 Climatology

3.1.1 Cold waves are generally experienced in the country during the period from November to March, but in some years they have also been observed during April and October as well, in certain regions.

3.1.2 Their frequencies, intensities and occurrences have already been studied by Raghavan (1967) based on 51 years' data from 1911 to 1961. Recent six years' data from 1962 to 1967 have been added to prepare the tables presented in this study.

3.2 General

3.2.1 As a whole, more cold waves are observed in the northwestern parts of India, and their frequencies fall considerably towards the southern and eastern parts of India. Like the heat waves, there are certain regions which do not experience these waves at all. These are Bay Islands, Lakshadweep, Tamil Nadu, Coastal and South Interior Karnataka, Coastal Andhra Pradesh and Kerala.

3.2.2 Jammu and Kashmir is the sub-division most affected by severe cold waves. The number of waves affecting this region is approximately 4 per year, but in the adjacent areas of Punjab and West Uttar Pradesh, the frequency of these waves falls significantly, being only one in two years. The most probable reason for this fall in frequency can be ascribed to the warming of the cold stream during its descent along the slopes of the high mountain ranges.

3.2.3 From Pakistan also these waves spread over the neighbouring parts of India. However, Rajasthan, West Madhya Pradesh and Saurashtra and Kutch have more incidence of cold waves than Punjab and West Uttar Pradesh. On an average, one severe cold wave per year may be expected to occur in Rajasthan and Kutch – Saurashtra area.

3.3 Frequency

3.3.1 The total number of severe cold waves experienced in each sub-division during the years 1911 to 1967 is given in Table 3. Regions susceptible to the severe cold waves are shown in Fig. 4(a) to 4(b). Their frequency and distribution are discussed below month by month.

TABLE – 3

Total number of severe cold waves (based on data 1911 to 1967)

Sub-division	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	Total
Assam					1			1
West Bengal			1	5	2	6		14
Orissa					3	2		5
Bihar Plains		1		4	1	4	2	12
Bihar Plateau	2	1	1	1	3	5	2	15
Uttar Pradesh, East				1	2	4	2	9
Uttar Pradesh, West		4	4	6	11	11	6	42
Punjab		1	4	7	6	10	6	34
Jammu-Kashmir		7	33	64	46	31	8	189
Rajasthan, East	1	4	8	17	12	9	10	61
Rajasthan, West		4	5	19	16	11	8	63
Madhya Pradesh, East			1	3	6	7	4	21
Madhya Pradesh, West		1	5	19	22	12	8	67
Gujarat		2	2	8	11	10	3	36
Saurashtra-Kutch	1	3	6	15	16	7	1	49
Madhya Maharashtra		1	3	8	13	3	2	30
Marathwada				3	2			5
Vidarbha			1	7	12	4	1	25
Telangana		1		1	1	2		5
Rayalaseema			2		1			3
Interior Karnataka, North		2	1	4	3			10
Total	4	32	77	192	190	138	63	696
% of Total	1	5	11	27	27	20	9	–

See Notes under Table 1.

3.3.2 October – There are only four severe cold waves recorded during the period under study. Generally this month is an insignificant month for these waves as there is hardly even 1% of occurrence of cold waves. The regions affected are also scattered i.e. Saurashtra and Kutch, East Rajasthan and Bihar Plateau (Fig. 4 b).

3.3.3 November - There are two distinct sectors in this month which are affected by these waves. One is in the western sector from Jammu-Kashmir to North Interior Karnataka. It is west of 80°E excluding Marathwada, Vidarbha and Rayalaseema. The other belt comprises of Bihar State (Fig. 4 c). In this month the frequency slightly increases and becomes about 5%.

3.3.4 December - This is the month in which these waves occur much in the southern part of the country like Rayalaseema; moreover areas like Marathwada, Telangana, Orissa, East Uttar Pradesh, Bihar Plains and Assam did not record any occurrence of these waves. The most susceptible area in this month is Jammu-Kashmir. The frequency over the country as a whole further increases to 11% and indicates the shift of its activity to include West Bengal (Fig.4 d).

3.3.5 January - In this month the frequency sharply rises to 27% and Jammu Kashmir remains most susceptible to these waves. There is considerable increase in Rajasthan, Madhya Pradesh, Gujarat State, Interior Maharashtra State and North Interior Karnataka. As far as Bihar State is concerned the activity starts in the Bihar Plains. It also commences in East Uttar Pradesh. The activity ceases in Rayalaseema but starts in Telangana (Fig. 4 e).

3.3.6 February - About 27% of the total number of incidences, are recorded in the month. The incidences reach a maximum in January and February. Almost all the areas included in Fig. 4 a which depicts the annual incidence are affected by cold waves during February (Fig. 4 f). It is seen that we cannot distinguish any part which is not susceptible during this month to be susceptible to cold waves during the year as a whole. The regions Vidarbha, Madhya Maharashtra, Gujarat Region, Madhya Pradesh and West Uttar Pradesh indicate significantly more activity of these waves than in January Jammu-Kashmir is still the most susceptible.

3.3.7 March - During this month, the frequency falls to 20%. Most of the Peninsular India becomes free from the occurrence of these waves (Fig. 4 g). Although the activity in Jammu-Kashmir becomes less, it remains the most susceptible area for the activity of these waves. In general, the incidences are less in the second part of the month.

3.3.8 April - This is the last month in the series; the frequency sharply falls to 9% of the total. The incidences practically cease from West Bengal and Orissa. The number of incidences becomes much less in Jammu-Kashmir (Fig. 4 h). In Rajasthan the number continues nearly the same.

3.4 Intensity

3.4.1 It may be recalled from what is written above that the lowest minimum temperature is not always experienced at a station in association with the severest cold wave, as the intensity of the cold wave is judged by the departure of minimum temperature from the normal. The lowest minimum temperatures ever recorded in each sub-division during the period from 1881 to 1967 are given in Fig. 5. It is seen from records that the lowest temperature of -45°C was experienced at Dras (in Jammu and Kashmir) on 28th December 1910. In the plains, the lowest temperature of -4.4°C has been recorded at Jaisalmer in West Rajasthan on 4th January 1949.

3.4.2 It has been noticed that generally the intensity of the cold wave decreases east of about Long. 80°E or south of Lat. 20°N. However, there is a small region south of 20°N, on the eastern side of the Western Ghats, where severe cold waves penetrate. This region comprises of Ahmednagar and Poona districts and the western part of Nasik. This may be due to the orography of the region. Raghavan (1967) explains it on the basis that the cold air collects in the valley at night, there being slopes on the three sides of the region. The movement of the air is restricted in that valley and the air which is trapped gets cooled further by radiation, and this phenomenon gets aggravated in this region when severe cold waves prevail over Gujarat.

3.4.3 During the months of January to March, 9°C to 10°C is the usual negative departure of minimum temperature associated with these waves in West Uttar Pradesh, West Rajasthan, West Madhya Pradesh and Saurashtra and Kutch area, but the cold waves of Jammu-Kashmir are very intense with the departure of minimum temperature of the order of -10°C to -12°C. Over rest of the country the intensity is of the order of 8°C to 9°C below normal. In certain exceptional cases the departures were more than 10°C below normal.

3.4.4 The severest cold wave in the country on record is of 23rd March 1911 in which Dras (in Jammu and Kashmir), has recorded a departure of -19.7°C. However, this wave was confined to a very small mountainous region of Ladakh. The severest cold wave in the plains prevailed from 30th January to 2nd February 1929. The maximum intensity of it was on 1st February 1929, when the departure dropped to 12°C below normal, over a considerable area in West Madhya Pradesh and the adjoining parts of Gujarat State and Madhya Maharashtra (Fig.6). During this wave, on 1st February 1929, the minimum temperature of -2.8°C at Indore in West Madhya Pradesh and -0.6°C at Malegaon in Madhya Maharashtra are the lowest ever recorded temperature in the respective sub-divisions.

3.5 Persistency

3.5.1 The maximum duration (i.e. the number of days) of severe cold waves is shown in Table 4.

TABLE - 4

Maximum duration (No. of days) of severe cold waves (based on data 1911 to 1967)

Sub-division	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Assam					2		
West Bengal			1	1	2	2	
Orissa					4	1	
Bihar Plains		1		1	1	1	4
Bihar Plateau	3	3	1	1	5	4	3
Uttar Pradesh, East				1	1	1	1
Uttar Pradesh, West		3	2	7	4	4	2
Punjab		6	4	3	3	4	3
Jammu-Kashmir		30	16	17	11	11	9
Rajasthan, East	1	1	2	8	4	3	4
Rajasthan, West		5	7	6	4	4	5
Madhya Pradesh, East			1	2	8	3	1
Madhya Pradesh, West		1	5	8	4	4	7
Gujarat		2	2	4	2	2	2
Saurashtra Kutch	2	1	6	5	4	3	1
Madhya Maharashtra		1	1	5	3	2	1
Marathwada				2	2		
Vidarbha			1	3	3	2	2
Telangana		2		1	1	1	
Rayalaseema			1		1		
Interior Karnataka North		1	1	1	1		

See Notes under Table 1.

3.5.2 In Jammu and Kashmir severe cold waves last for a period of 4 to 5 days, but in the month of April it does not last more than a day. In

Rajasthan, Saurashtra and Kutch and West Madhya Pradesh they last for a shorter period i.e. 2 to 3 days particularly in January, but in other areas usually they persist for a day or two. The longest duration of 30 days has been recorded for a severe cold wave but it was confined to a small area of Ladakh in Jammu and Kashmir.

3.6 Extent of coverage

3.6.1 During the period from January to March, severe cold waves generally prevail at a time, over an area of 5,00,000 sq. km. In the other months, the area covered is small and of the order of 2,00,000 sq.km. But in Jammu and Kashmir, severe cold waves are mostly confined to small areas of Ladakh. It has been noticed also that the greater the intensity of the wave, the smaller the area it covers at a time. Of all the cold waves recorded so far, the wave that occurred on 12th February, 1950, prevailed over the largest area. It can be seen from Fig. 7 that the whole of North India from Rajasthan to West Bengal was in the grip of this wave.

3.7 Factors favourable for cold waves and associated synoptic situation

3.7.1 It is seen that cold waves occur due to the inflow of very cold air from northern latitudes i.e. from the extreme northwestern parts of the Indian sub-continent or even beyond. When this unusually cold air spreads over other parts of the country, it manifests as a "cold wave" in those parts. Thus, any pressure system or synoptic situation, which is capable of causing an inflow of cold air from these northern latitudes into India will create favourable conditions for incidence of cold waves.

3.7.2 While discussing the favourable synoptic situations which lead to the incidence of cold wave conditions in India, Mooley (1957) has summarised as follows. "If there is to be a free and rapid flow of very cold air from considerably northerly latitude, it is necessary that the disturbance which is moving away across India should be deep, i.e. the negative pressure departure from normal should be sufficiently large and there should be no other disturbance in the rear affecting India and no disturbance to the north of India. The absence of a disturbance to the north of India for a few days will ensure flow of air from considerably northerly latitudes while the absence of a following disturbance in the rear will ensure that there will be no inflow of warm air over northwest India from southerly latitudes. In other words, the absence of a disturbance to the north of India causes a marked cold wave over north and central India and absence of disturbance to the rear allows the intensity of cold wave to be maintained for sufficient time".

3.7.3 Situations as mentioned above may not always be realised in association with every western disturbances and perhaps this may be one of the reasons for cold wave conditions not being experienced in association with each and every western disturbance. But, whenever the cold wave conditions develop,they are invariably associated with western disturbances manifesting in some form or the other. This being the case, it is necessary to examine the thermal structure of the trough systems associated with the western disturbances in order to understand the mechanism which produces cold wave conditions.

3.8 Trough in the upper westerlies

3.8.1 The western disturbances in their active stages generally manifest over India as low pressure systems either affecting the lower or the upper tropospheric levels, and sometimes both. A well-marked trough in the upper westerlies is more or less a common feature associated with the systems of western disturbances. In the vicinity of the axis of these troughs, the existence of a pool of cold air in the upper levels can often be traced. This pool of cold air invariably travels with the troughs and sometimes it is also seen to spread into lower levels to reach the ground to manifest as surface cold waves.

3.8.2 In accordance with the degree of anomaly of temperature in the associated cold pool of air, the westerly troughs which travel across north India during winter months can be classified under three main groups.

(a) Severe Cold-core Trough – (S.C.C.). If algebrically the prevalent temperature anomaly in the cold air is −6°C or less at all levels in the affected layer, it will be considered as Severe Cold-core Trough.

(b) Moderate Cold-core Trough (M.C.C.) – If algebrically the prevalent temperature anomaly in the cold air is −1°C to −5°C at all levels in the affected layer, it will be taken as Moderate Cold-core Troughs (M.C.C.); sometimes anomaly less than −5°C is also observed at one or two levels in the affected layer.

(c) Warm-core Troughs (W.C.) – If algebrically the prevalent temperature anomaly in the cold air is −1° to +4°C at all levels in the affected layer, it will be considered as Warm-Core Trough (W.C.).

3.8.3 The chief characteristics of these main groups are shown in tabular form in Table 5.

3.8.4 To find out the temperature anomaly at various levels for different radiosonde stations in India, the mean monthly values of dry bulb temperatures at different levels have been worked out from 7 years data (1959–1964) of these stations and utilised in the present study. The actual dry bulb temperature values at 0001 GMT over a station on a particular day when subtracted algebrically from the corresponding mean monthly values, level by level, give the values of temperature departures at various levels, for that station. A typical trough belonging to each of the three groups is illustrated in Appendix II. These are depicted by the vertical time-sections with temperature and anomaly of temperature profiles.

TABLE – 5

Sr. No.	Category of Trough	No. of cases examined	Depth of the cold pool	Affected Layer	Prevalent Temp. anomaly in the cold air	Chief characteristic features of the trough and other remarks
1	2	3	4	5	6	7
1.	Severe Cold-core Trough (S.C.C.)	17	6 to 9 km	Generally from ground upto 400 to 300 mb	$-6^{\circ}C$ or more at all levels in the affected layer	i) In these troughs, the pool of cold air generally possesses a pronounced vertical tilt to the east w.r.t. their axis. ii) Generally associated with western disturbances. iii) Generally produce severe cold wave conditions at the surface iv) They have utility from the point of forecasting surface cold wave conditions.
2.	Moderate Cold-core Trough (M.C.C.)	19	2 to 4 km	Sometimes lower tropospheric and sometimes Upper Tropospheric layer	$-1^{\circ}C$ to $-5^{\circ}C$ at all levels in the affected layer. Sometimes anomaly less than $-5^{\circ}C$ is also observed at one or two levels in the affected layer.	i) In these troughs, the vertical tilt of the associated cold air is not so pronounced as in the cases of S.C.C. Troughs ii) Sometimes they are associated with active western disturbances iii) They are somewhat useful from the point of forecasting surface cold wave conditions when they are embedded in the lower tropospheric layer (from ground upto 700/600 mb).
3.	Warm-core Trough (W.C.)	4	3 to 5 km	As in M.C.C. Trough	$-1^{\circ}C$ to $+4^{\circ}C$	i) They are generally associated with weak western disturbances ii) They do not produce cold wave conditions iii) They are very rarely observed.

3.9 Thermal structure of cold wave troughs

3.9.1 It is seen from Table 5 that generally surface cold wave conditions develop with the passage of almost all severe cold core (S.C.C.) troughs and those moderate cold-core (M.C.C.) troughs which are embedded in the lower tropospheric layers. The M.C.C. troughs which travel only as a trough in the upper troposphere, may not produce any cold wave conditions at the surface. Rai, Sircar and Datar (1963) have pointed out this feature of M.C.C. troughs and their consequent inability to produce cold wave conditions at the surface.

3.9.2 The delineations of the contour and isotherms around a severe cold-core trough at different isobaric levels on 7th February 1961 are depicted in Appendix III.

3.9.3 An analysis of synoptic situations associated with different cold waves experienced in the country during the period 1945-67 has been made. It is seen from the analysis that in more than 95% cases, the cold waves are associated with western disturbances.

3.9.4 A case of a cold wave situation which is not associated with a western disturbance but with a low pressure area over the North Arabian Sea is depicted in Fig. 8 (a and b).

3.9.5 From figure 8(a) it is seen that there is an anticyclonic flow in the lower troposphere over the western parts of Pakistan and the associated ridge line runs through north Rajasthan to northwest Madhya Pradesh. In association with the low over North Arabian Sea, it provides the flow pattern which transports the colder air from northern latitudes to the region affected by this moderate cold wave indicated in Fig. 8(b).

3.9.6 After the passage of western disturbances, due to the cooling of the ground at night, normally radiation fog develops. It generally lifts up later in the morning but may remain on some rare occasions as stratiform clouds till afternoon thereby inhibiting the insolation on the ground. It results in further lowering of temperatures and making the cold wave more intense. Practically this process goes on repeating daily till the northwesterly strong cold wind sweeps the area.

3.10 Forecasting surface cold wave conditions

3.10.1 From the chief features of the cold core troughs mentioned in the previous sub-sections and Appendix II, it appears that cold air associated with these troughs has a fairly pronounced tilt to the east in the vertical with respect to the axis of the trough. On account of this characteristic of the cold-core troughs, it is observed that cold wave conditions generally develop at upper levels at stations situated far to the east of the trough axes much earlier (i.e. about 12 to 36 hours) than they do so at the surface levels at these stations. This characteristic feature is noticeable in most (about 80%) of the severe cold-core troughs and some (about 40%) of the moderate cold-core troughs.

3.10.2 Thus, if we observe advection of cold air at upper levels (in the layer 600 to 300 mb) in the temperature sounding of a station where approach of a cold-core trough is expected, we can predict with a fair degree of accuracy the occurrence of surface cold wave conditions in the area represented by that station in the next 12 to 36 hours. The above feature of cold-core troughs serves as an additional tool for predicting surface cold wave conditions.

3.11 Movement of cold waves

3.11.1 When the western disturbances move northeastwards across the northern parts of Pakistan and the adjoining Northwest India, the associated cold wave conditions do not generally spread much to the south but remain confined to Punjab, Himachal Pradesh, Northwest Uttar Pradesh and North Rajasthan.

3.11.2 But when the induced lows of the western disturbances move eastwards across north India the associated cold wave conditions appear over different parts of north India and Central India even as far south as 20°N latitude.

3.11.3 When these western disturbances move away eastwards from northwest India, the normal low level anticyclonic flow in the swept area re-establishes. On many occasions under the influence of this low level anticyclonic circulation and the associated cyclonic circulation of the eastward moving western disturbance, northerly or north-westerly winds are established in lower levels in the region intervening the two systems. These strong winds help to spread surface cold wave conditions more and more into southern latitudes. This point is discussed in detail in Appendix III. It is also shown in the same appendix that sometimes the southward progress of cold waves is prevented by the inflow of moist air in the lower levels.

3.11.4 As illustrated and mentioned in Appendix II while discussing Fig.12, the warming processes resulting in dissipation of cold wave conditions begin to operate first from the top layers of the cold pool. The dissipation,thereafter, sets in over successive lower layers and finally at the surface. Since the warming processes have a tendency to operate in a downward direction, the surface cold wave conditions generally tend to persist for a longer time,i.e. 2 to 3 days, than those at upper levels. Surface cold wave conditions, however, disappear very quickly with the advection of moisture-laden winds in lower levels (Appendix III).

APPENDIX - I

1. Severe Heat Wave of June 7-12, 1966.

1.1 The temperatures were generally above normal during the first fortnight of the month in the whole of India except the southern tip and eastern part of Assam. The severe heat wave which was experienced during this fortnight from 7 to 12th June 1966 recorded the highest departure of +11°C at a few stations in Bihar and West Bengal, but it has not given any highest maximum temperature record anywhere. It was mostly confined to Bihar and Uttar Pradesh. Then the anomalies weakened after 12th June 1966.

1.2 All the data covering this period has been taken from the IDWR for preparing the charts in this Appendix.

1.3 The +6°C temperature anomaly isopleth on the 6th June, 1966, one day earlier to the incidence of the severe heat wave, was covering the wide area comprising of East Rajasthan, northern half of Madhya Pradesh, Bihar Plains, East Uttar Pradesh, southern part of West Uttar Pradesh and a small area of Himachal Pradesh. Then on seventh, though the +6°C temperature anomaly isopleth was covering the same area, the severe heat wave of +8°C anomaly was over Bihar Plains and East Uttar Pradesh. The area covered by the wave was practically the same on eighth, but on ninth it was confined to Bihar State only and it showed some movement towards east covering West Bengal also. On tenth, conditions were nearly the same and the highest temperature of this fortnight were recorded on these two days (9th and 10th). Almost the whole of West Bengal and some portion of north Orissa also came under the grip of the heat wave. Practically the same area of West Bengal and Orissa was covered on eleventh also. On twelfth, only a small portion in the central part of West Bengal was affected and on thirteenth the heat wave disappeared from the chart.

2. Synoptic conditions

2.1 On the surface chart the pattern was normal as it should be in June. During this period of severe heat wave the trough was running along the Gangetic Plains and a dynamic trough was along 80°E longitude.

2.2 Initially, for instance on 4th, at 500 mb level, there were two highs, one covering the area of Gujarat, Saurashtra and Kutch and Rajasthan and another on the east coast blanketing the area of Orissa, North Coastal Andhra Pradesh, South Bihar and some southwest part of West Bengal and it also covered West Central Bay and head Bay, which resulted in a feeble trough over West Uttar Pradesh. As a result, it gave an anticyclonic flow over East Uttar Pradesh, Bihar State and West Bengal. When the trough moved eastward, another trough appeared over Pakistan area giving strong anticyclonic flow over the region. The centre of the high pressure area was over the east coast enveloping the entire Peninsula and Bay of Bengal. After the tenth, the trough moved rather fast and on 12th June 1966 it was over Bihar with two anticyclones on the two sides, one in the Arabian Sea spreading anticyclonic flow over the entire Peninsula and another over Burma and Thailand.

2.3 The main purpose of this Appendix is to show the relation of the severe heat wave with the thicknesses in the lower and middle troposphere. The pressure systems in the intermediate levels are not so essential to discuss. The various thicknesses and their departures from normal are dealt with in full below. What is essential to produce a heat wave is mainly how the increased thicknesses resulting from the warming of the layer, are advected to the regions where the severe heat waves are experienced. The winds which will indicate the transport of the warm air in the lower and middle troposphere are northwesterly to westerly, north of 20°N. That is the moderate westerly component is maintained during the period, which aids the eastward transport of warm air; and moreover as the flow was completely continental, no moisture could penetrate over the concerned region where the severe heat wave was experienced.

3. Data

3.1 In this appendix, 1200 GMT charts for three days have been selected in such a way that the first day presents a day earlier to incidence of the severe heat wave, the second day was the most intense day for the severe heat wave and the third day was the last day of the severe heat wave. These are presented in Fig.9,10 and 11. To prepare these charts, normals for these two pentads (1) from 6 to 10th and (2) from 11 to 15th June were prepared based on the seven years (from 1961 to 67) data, taken from the I.D.W.R.

3.2 In these three charts

i) Figure (a) shows the extent of temperature anomaly (+6°C) which indicates the area covered by the moderate heat wave and the extent of temperature anomaly +8°C shows the area of severe heat wave.

ii) Figure (b) indicates the sea level charts at 1200 GMT (solid line) and 1000–500 mb departure from normal thickness pattern (dashed lines) for 1200 GMT of those dates.

iii) Figure (c) shows 500 mb contours (solid lines) and departure from normal (dashed lines) for 1200 GMT for those days.

iv) Figure (d) depicts 500 mb height change (solid lines) and 1000–500 mb thickness change charts (dashed lines) for 1200 GMT for those days. Height values on all the charts are in tens of metres.

3.3 All the charts presented in this appendix show the transport of warm air in the concerned region. Similar transport of warm air also took place in the northern region of Andhra Pradesh but probably due to the clouding and moisture bearing sea-breeze currents the heat wave did not occur.

4. Conclusion

4.1 Thus, the necessary parameters for the formation of this severe heat wave were present viz. – height and thickness values considerably above normal at all levels; a source region of warm air and appropriate flow pattern for transportation of warm air over the region; no moisture in the upper air over the area, leaving the sky practically cloudless to allow maximum insolation, and lastly the large amplitude anticyclonic flow over the region.

APPENDIX - II

1. Troughs in Westerlies

1.1 The troughs in westerlies are divided into three categories and their chief features have been given in Table 5 (Section 3). Typical examples of these troughs (one each) have been illustrated by Figs. 12,13 and 14 respectively.

2. Severe Cold Core Trough

2.1 The vertical time-section for Jodhpur for 17-24 January 1962 with temperature and anomaly of temperature profiles in respect of the severe cold core trough which caused severe cold wave conditions over Rajasthan and adjoining areas of Madhya Pradesh is shown in Fig. 12.

2.2 In this figure, the morning's vertical temperature profile and the corresponding temperature anomaly profile for each date are shown by continuous and dashed lines respectively. Taking the vertical line through 0001 GMT of the particular date as the reference line to represent the 0°C isotherm for the temperature profile and no anomaly line for the anomaly profile, the temperature and anomaly profiles for that date are suitably drawn after reckoning that temperatures (and also their anomalies) have positive values to the right of the reference line and vice-versa. The temperature and anomaly profiles for other dates are also drawn in a similar manner. The distance between two successive reference lines represents an interval of 10°C in this figure. The upper air trough is indicated by a thick continuous line and the domains of cold air (of anomaly -6°C or less) for each date are stippled.

2.3 It is seen from this time-section that the upper air trough passed through Jodhpur on the night of 20th. Other important features noticeable in the time-section are:-

i) Cold air (of anomaly −6°C or less) was not present in the troposphere over Jodhpur on 18th and 19th. The anomaly profiles, on these two days, were lying mostly to the right of their respective reference lines, indicating that air over Jodhpur was warmer than usual on these two days.

ii) On 20th morning (about 18 hours before the passage of the trough), cold air (of anomaly −6°C or less) appeared in the upper levels over Jodhpur but had a limited depth from about 600 to 490 mb (see the extent of the stippled area on 20th). In lower levels, less cold air (of anomaly less than −6°C) was, however, present.

iii) With the passage of the trough on the night of 20th, a fairly deep layer of cold air (from ground upto 500 mb) appeared over Jodhpur and simultaneously moderate to severe cold wave conditions developed over surface layers.

iv) Surface cold wave conditions persisted till the 23rd although cold wave conditions in the upper levels started dissipating from 22nd morning. Finally on 24th, cold wave conditions both at the surface and in the upper levels dissipated away.

v) With the advection of the layer of cold air first in the upper levels (on 20th) and then in the lower levels (on 21st) and thereafter with the progressive reduction in the depth of the cold air (on 22nd and 23rd), the base 'B' of the isothermal-cum-inversion layer 'AB' associated with this cold air also came down successively from 510 mb on 20th to 650 mb on 21st, 800 mb on 22nd and 900 mb on 23rd.

vi) The lapse rate within the layer of cold air (of anomaly −6°C or less) was comparatively less than in the air aloft.

3. Moderate Cold Core Trough

3.1 An example of a moderate cold core trough which travelled only through the layers of upper troposphere is shown in Fig. 13. It has already been mentioned that this type of trough may not produce any cold wave conditions at the surface. It is seen from the time-section of Delhi between 19th and 22nd January 1959 that the trough passed across Delhi on the night of 20th.

i) At each level the dry bulb temperature is plotted on the top of the level point and its anomaly at the bottom.

ii) The axis of the trough is shown by a continuous thick line.

iii) The domain of cold air (of anomaly -3°C) is shown by a dashed line.

4. Warm-Core Trough

4.1 In Fig. 14, a time-section of Jodhpur between 1st and 3rd February, 1960 is shown. This is an example of a warm-core trough, which normally does not produce cold wave conditions at the surface. Temperature and anomaly are plotted as in Fig. 13. The domain of warm air of +4°C anomaly is marked by a dashed line.

APPENDIX - III

1. Thermal Structure of Cold Wave Trough

1.1 The delineation of the contour and isotherms around a severe cold-core trough at different isobaric levels on 7th February 1961 is depicted in Fig. 15 (a) to (g). In association with this trough, moderate to severe cold wave conditions were experienced on the morning of 8th February over a wide area in northwest and central India. (Figs 15h and 15i)

1.2 It is interesting to see from these figures that the cold pool of air (of anomaly -6°C) was confined to the area to the left of the axis of the trough at lower levels (Fig. 15 a and 15 b). But in higher levels, the cold air gradually delineated itself in an east-west direction and part of it moved to the area lying to the right of the axis of the trough (at least in the northern portion of the trough); and finally at 300 mb level, the cold air confined itself in an area lying entirely to the right of the axis of the trough at this level. The positioning of the pool of cold air, level by level, with respect to the axis of the upper air trough as seen in these figures suggests the possibility of the cold air dome tilting forward in the vertical with respect to the axis of the trough. This feature can be utilised in predicting surface cold wave conditions. This has already been discussed in Section 3.10.

1.3 A vertical west-east cross section along 25°N latitude at 0001 GMT on 8.2.1961 through another S.C.C. trough is depicted in Fig. 16. It can be seen from this figure that cold air is having a pronounced tilt to the east in the vertical with respect to the axis of the trough, particularly at upper levels.

1.4 When a western disturbance moves away eastwards, in the rear of this disturbance, the normal low level anti-cyclonic flow re-establishes. It is clear from Fig. 17(a) which indicates the flow pattern at 0230 GMT on 23rd January 1953 at 600 m. asl, that the strong winds between the two systems - one a cyclonic circulation over West Bengal and adjoining Assam and another an anticyclonic circulation over Punjab and Pakistan area – spread eastward and southward. Surface cold wave conditions moved to the southern latitudes. In Fig. 17(a) the dashed line is the boundary of the area affected by surface cold wave on 24th January 1953 at 0230 GMT. Fig. 17(b) shows the same band of strong winds spreading into more southern latitudes than on the previous day, consequently shifting the southern boundary of the surface cold wave area to further south.

1.5 On many occasions, the southward progress of these cold waves is arrested by inflow of moist air in the lower levels. The same interesting point is illustrated in Fig. 18 wherein the flow pattern at 0001 GMT on 22nd January 1962 at 900 m asl is depicted. The dotted and hatched curves show the boundaries of surface cold wave area on the morning of 22nd and 23rd January 1962 respectively, but with the inflow of moist air from the Bay on the morning of 22nd, movement of cold wave into more southern latitudes on 23rd is arrested.

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DIAGRAMS

FIG. I REGIONS SUSCEPTIBLE TO SEVERE HEAT WAVES

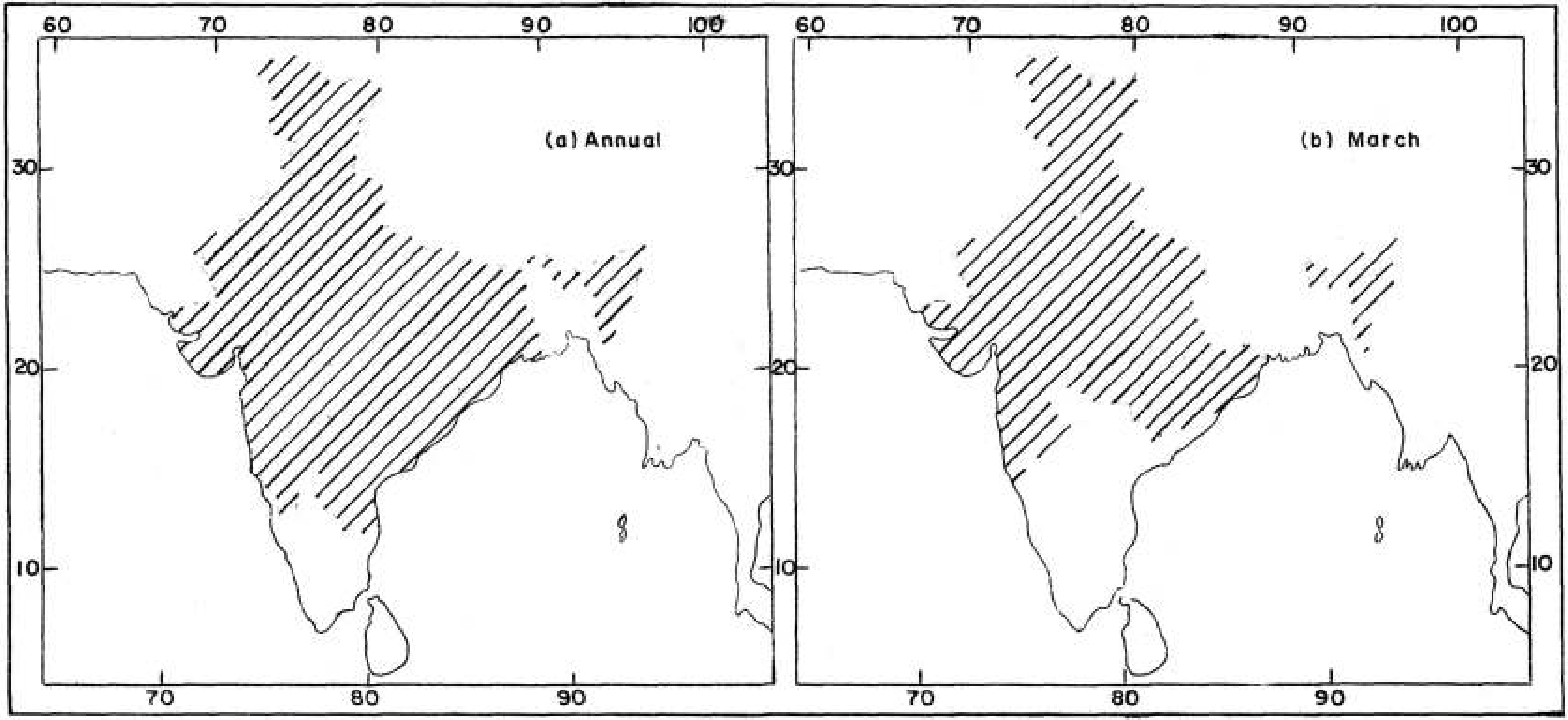


FIG. I (Contd.)

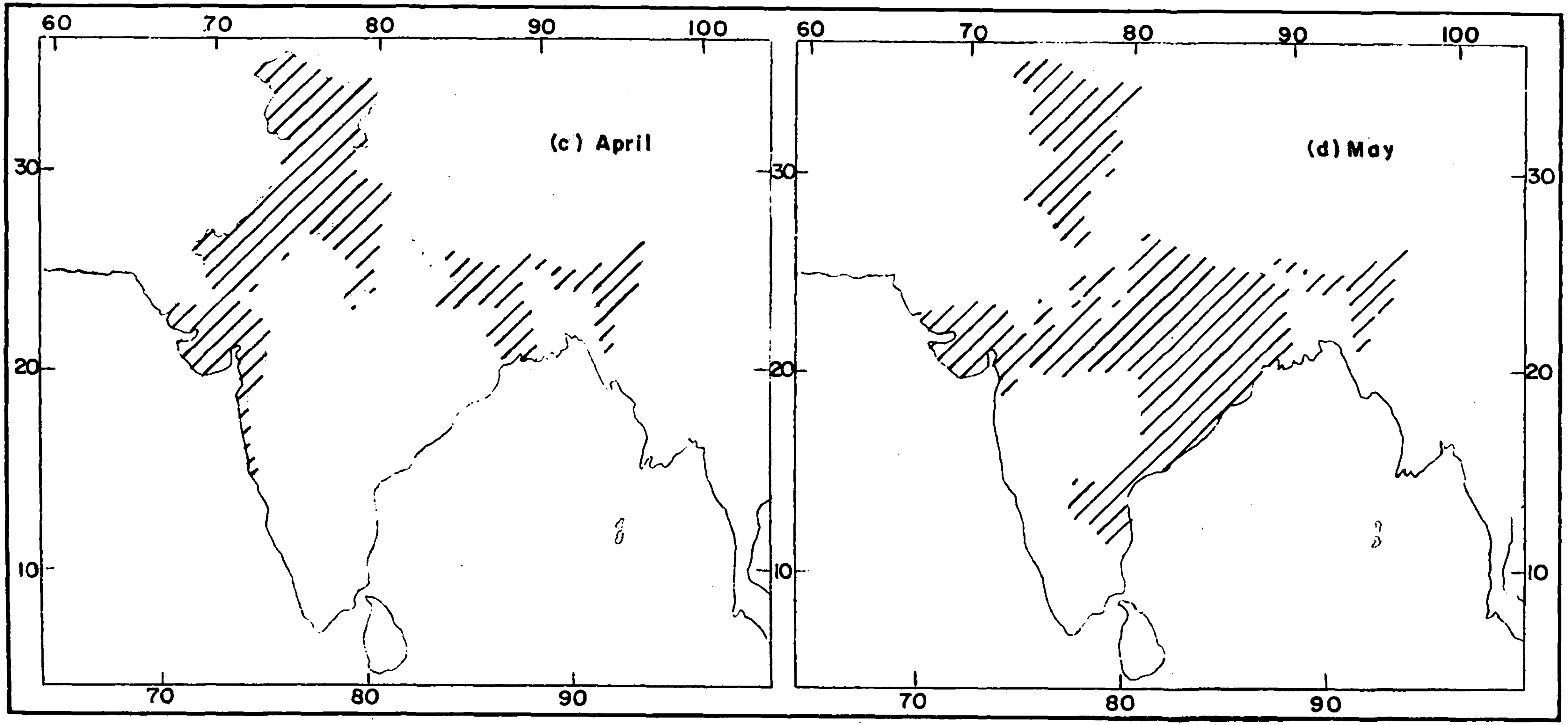


FIG. I (Contd.)

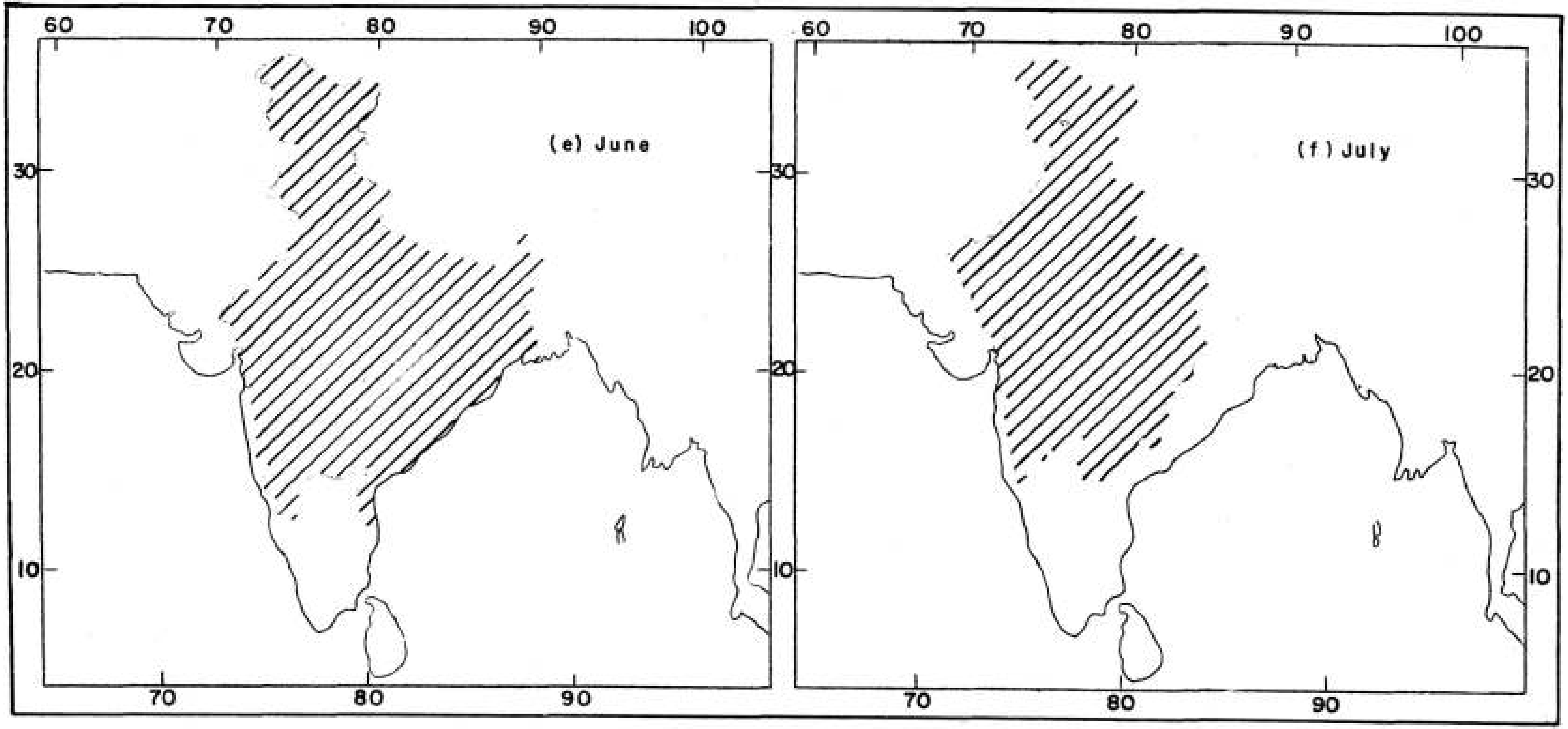


FIG. 2 HIGHEST MAXIMUM TEMPERATURE (°C) EVER RECORDED IN INDIA DURING THE YEARS 1881 TO 1964

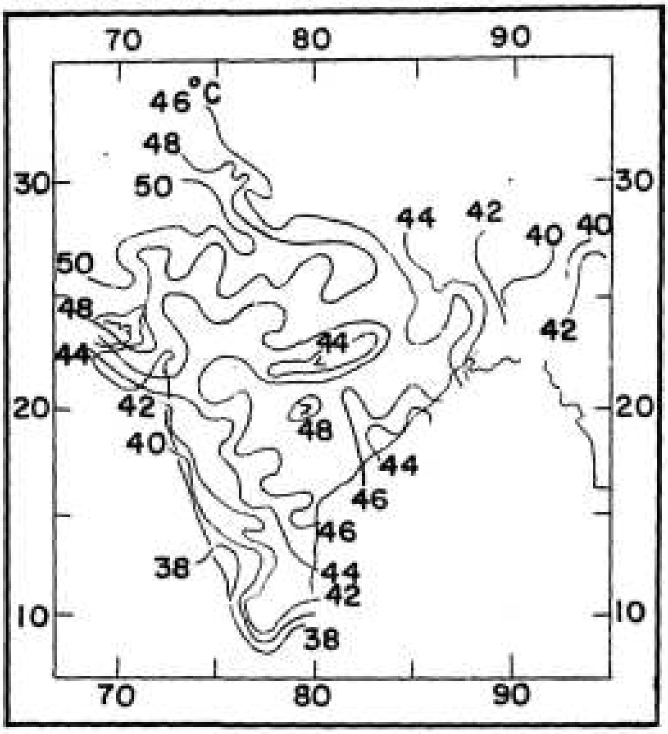
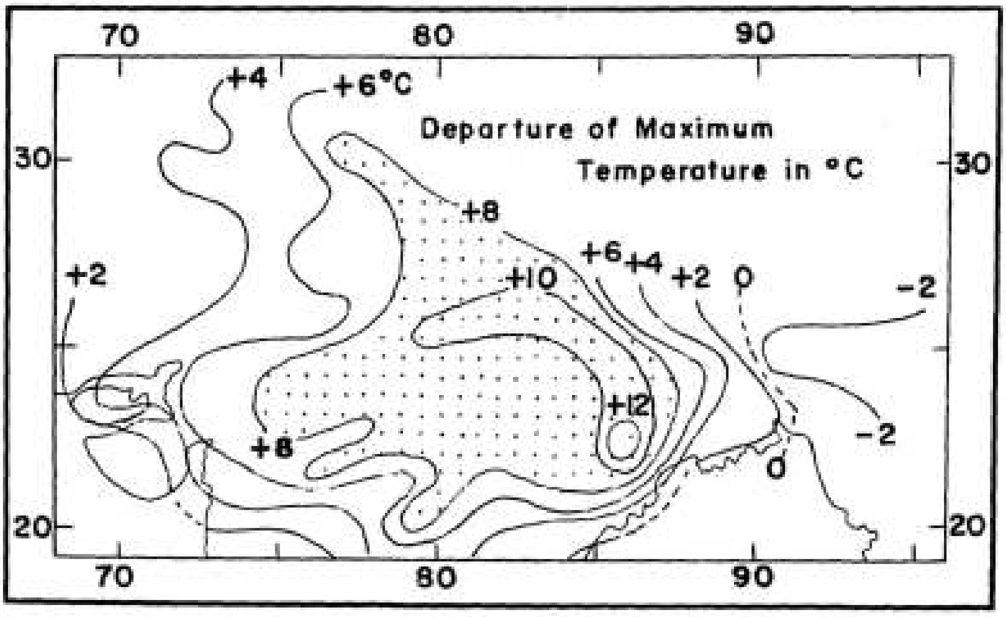


FIG. 3 SEVERE HEAT WAVE OF THE LARGEST EXTENT ON 26 JUN. 1926.



(Reproduced from "A climatological study of Severe Heat Waves in India" by K. Raghavan, IJMG, 1966, Vol.17, No.4, pp.581-586)

FIG. 4 REGIONS SUSCEPTIBLE TO SEVERE COLD WAVES

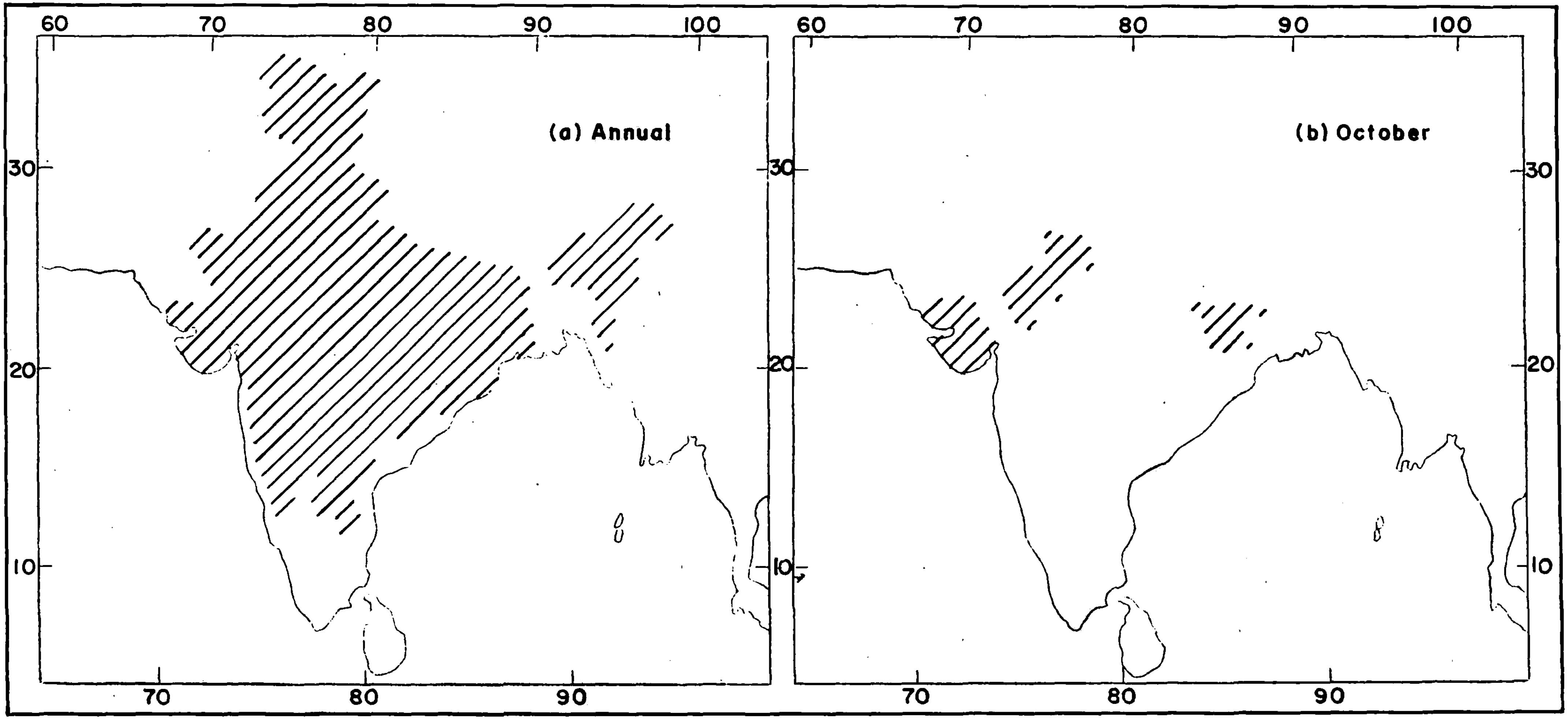


FIG. 4 (Contd.)

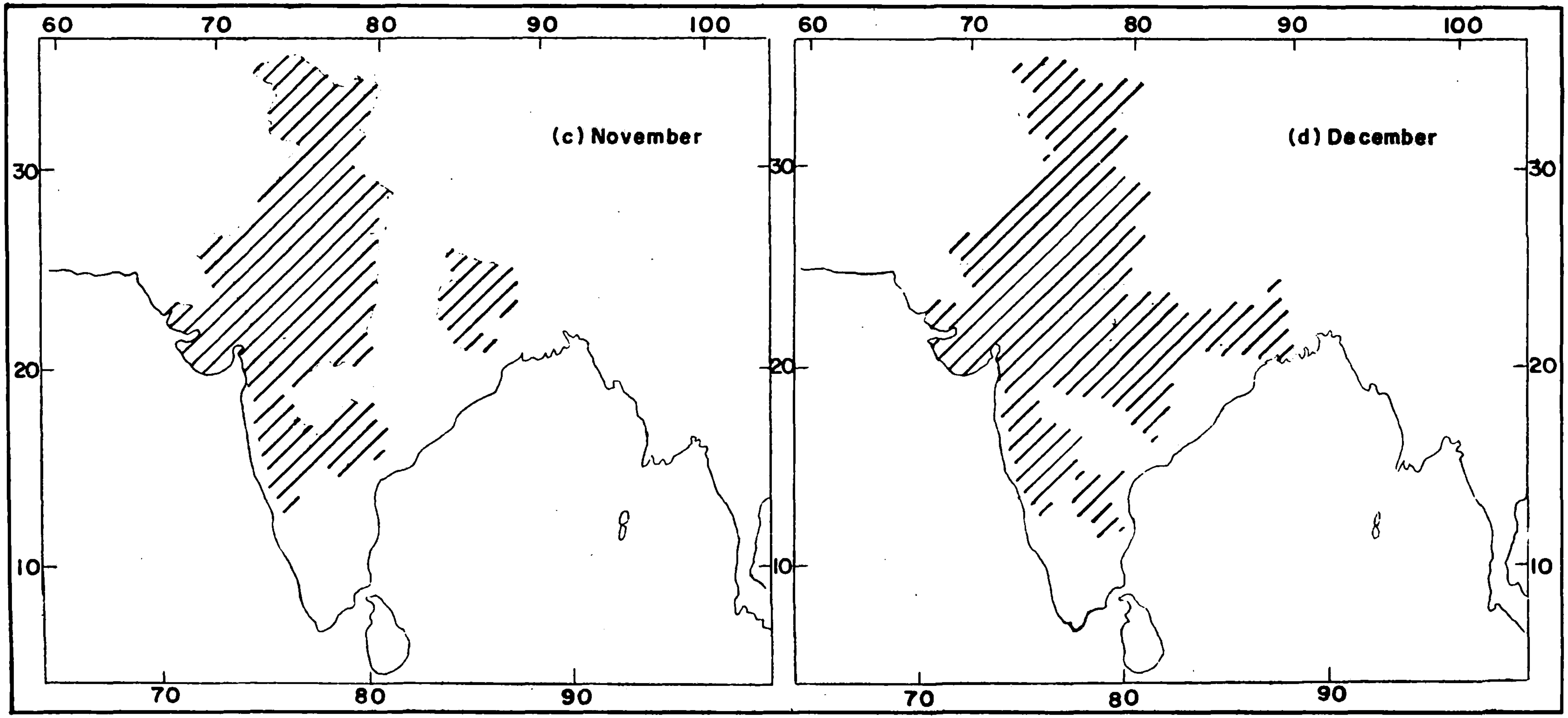


FIG. 4 (Contd.)

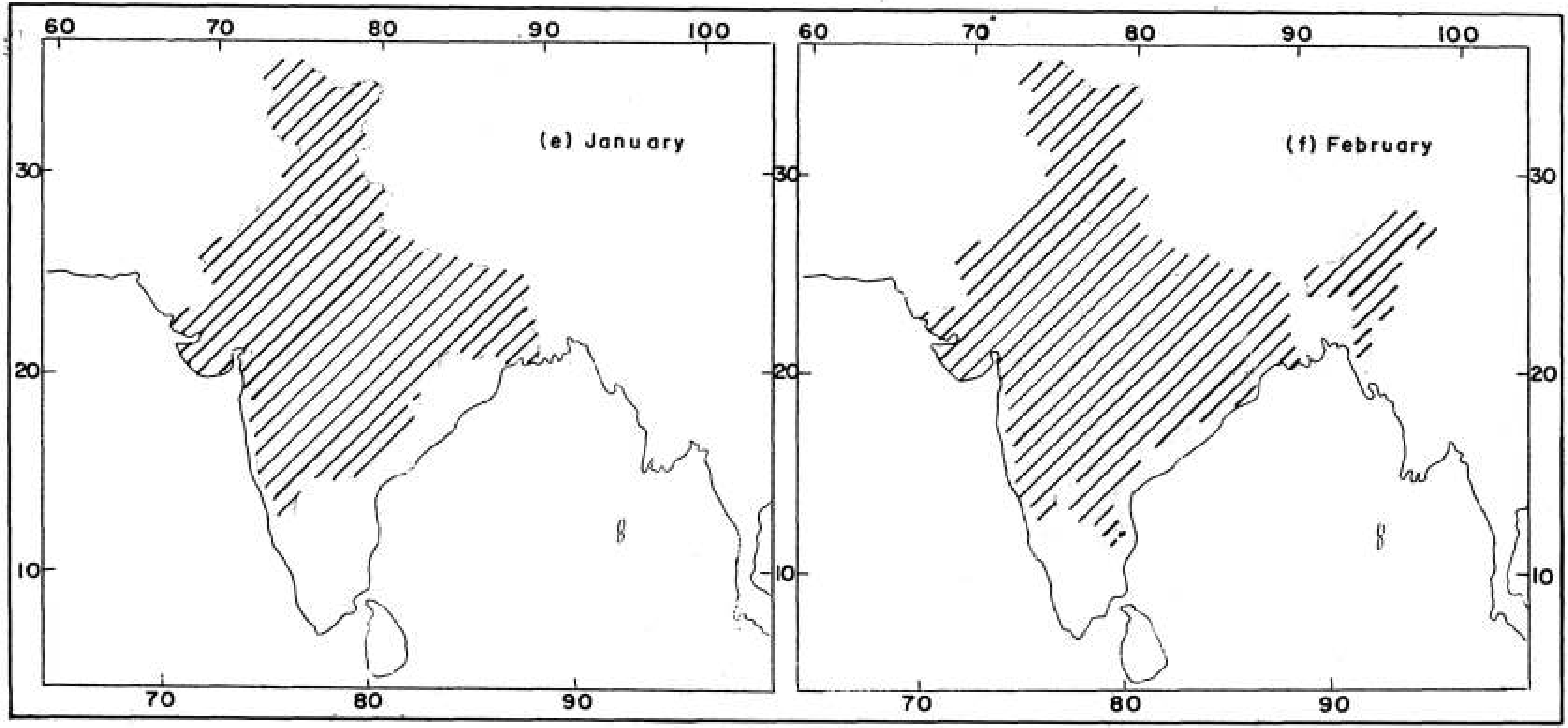


FIG. 4 (Contd.)

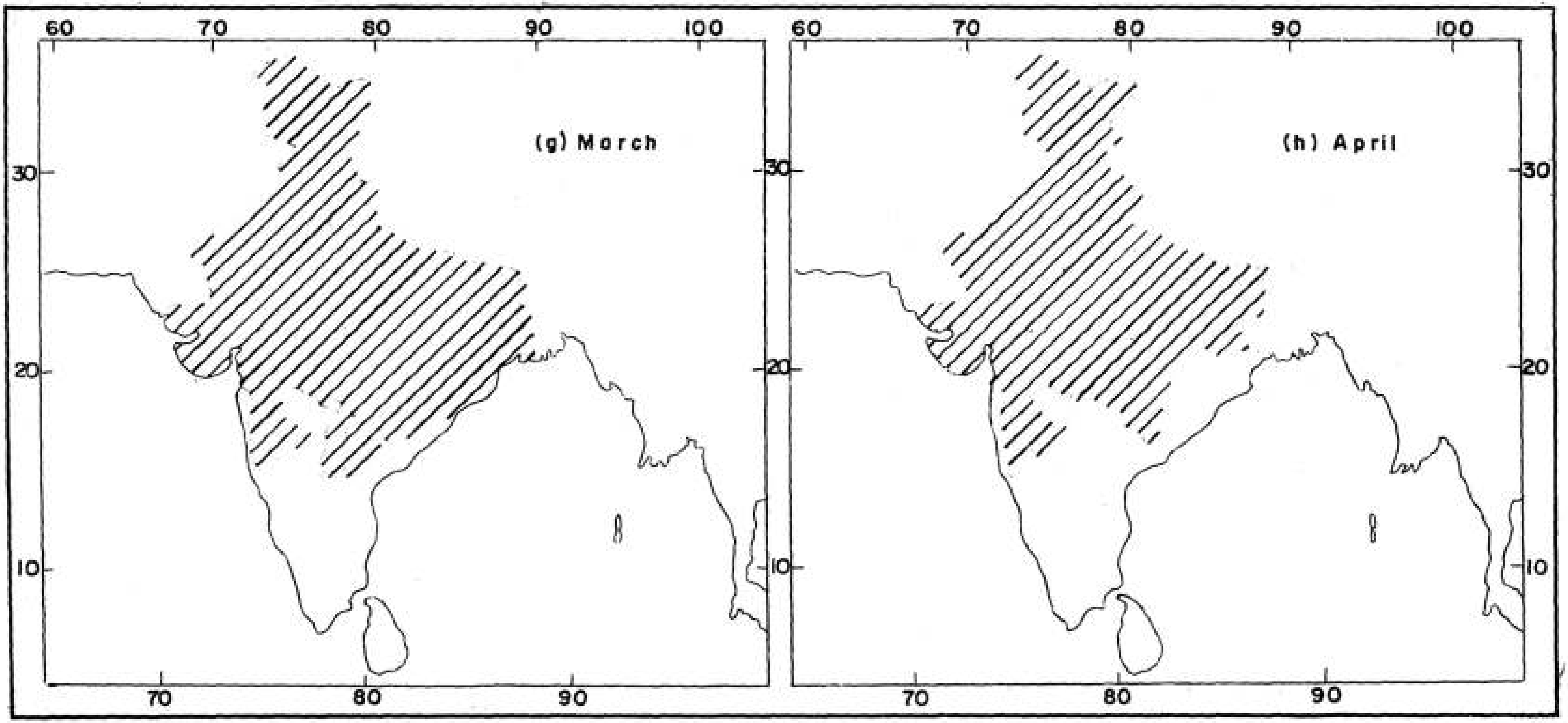


FIG. 5 LOWEST MINIMUM TEMPERATURE (°C) DURING THE YEARS 1881-1967

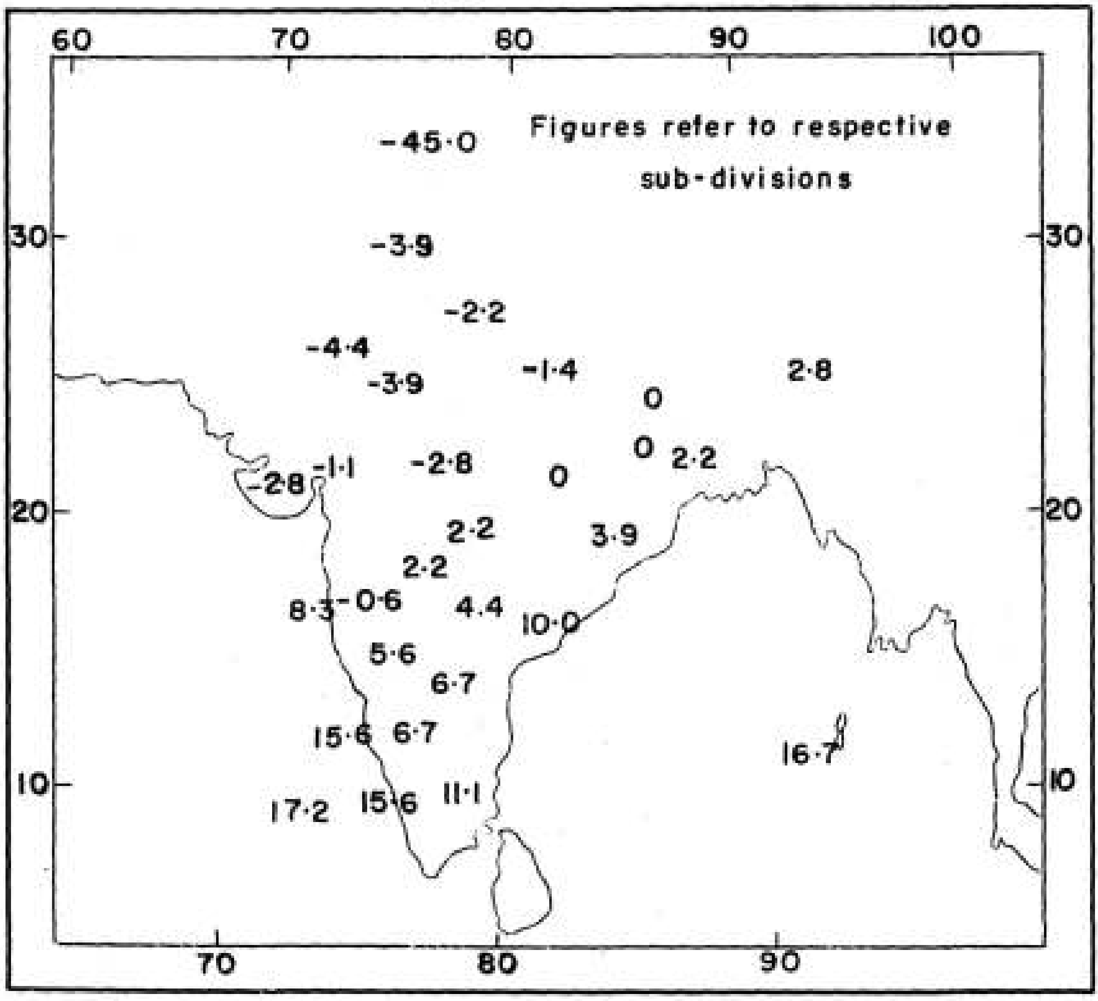
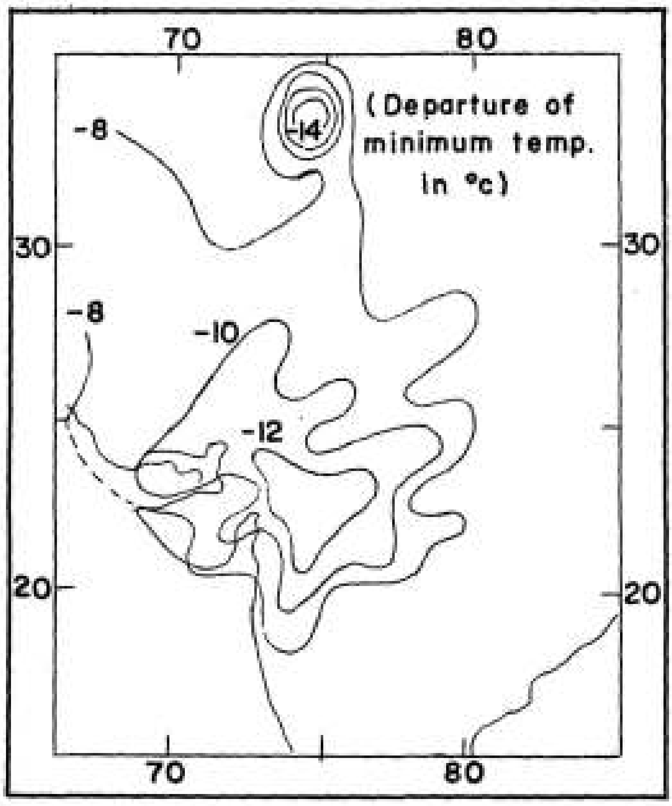


FIG. 6 SEVEREST COLD WAVE IN THE PLAINS OF INDIA ON 1 FEB. 1929

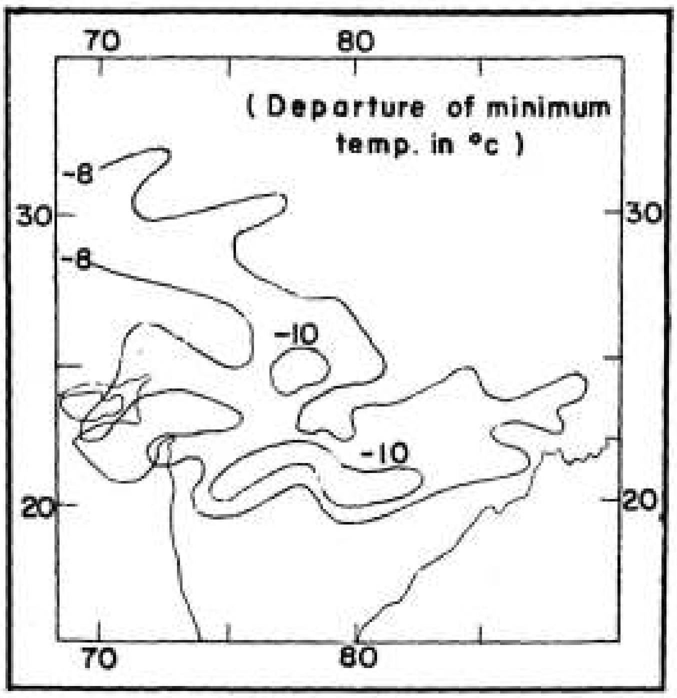


(Reproduced from "A climatological study of severe Cold Waves in India" by K.Raghavan, IJMG, 1967, Vol.18, No.1 : pp 91-96)

FIG. 7

SEVERE COLD WAVE OF THE LARGEST EXTENT IN INDIA ON

12 FEB. 1950



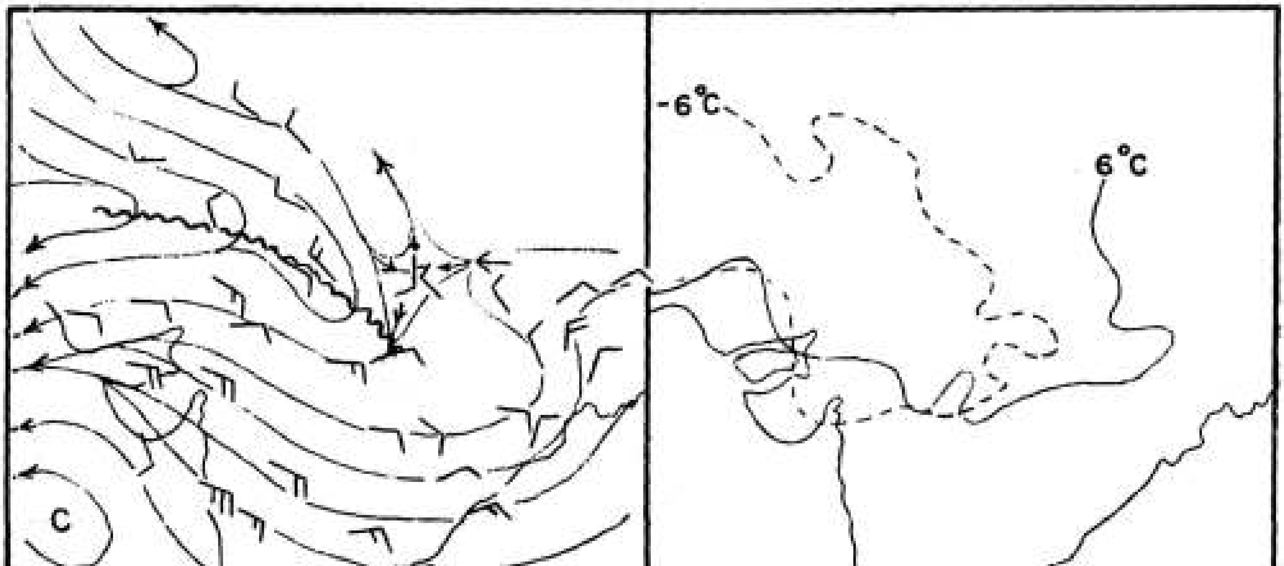
(Reproduced from "A climatological study of severe Cold Waves in India" by K. Raghavan, IJMG, 1967, Vol.18, No.1, pp 91-96)

FIG. 8

A COLD WAVE SITUATION NOT ASSOCIATED WITH A WESTERN DISTURBANCE, BUT WITH A LOW PRESSURE AREA OVER NORTH ARABIAN SEA

(a) Flow pattern at 900 m.a.sl. on 14 Dec. 1954 (0230 Z)

(b) Minimum temperature and its departure from normal on the morning of 15 Dec. 1954



———— Isopleth of 6°C isotherm

- - - - - - Isopleth of -6°C departure from normal

C - Centre of cyclonic circulation

~~~~~ Ridge line
~~~~~

Fig.9(a) : Area affected by moderate heat wave on 6 June 1966

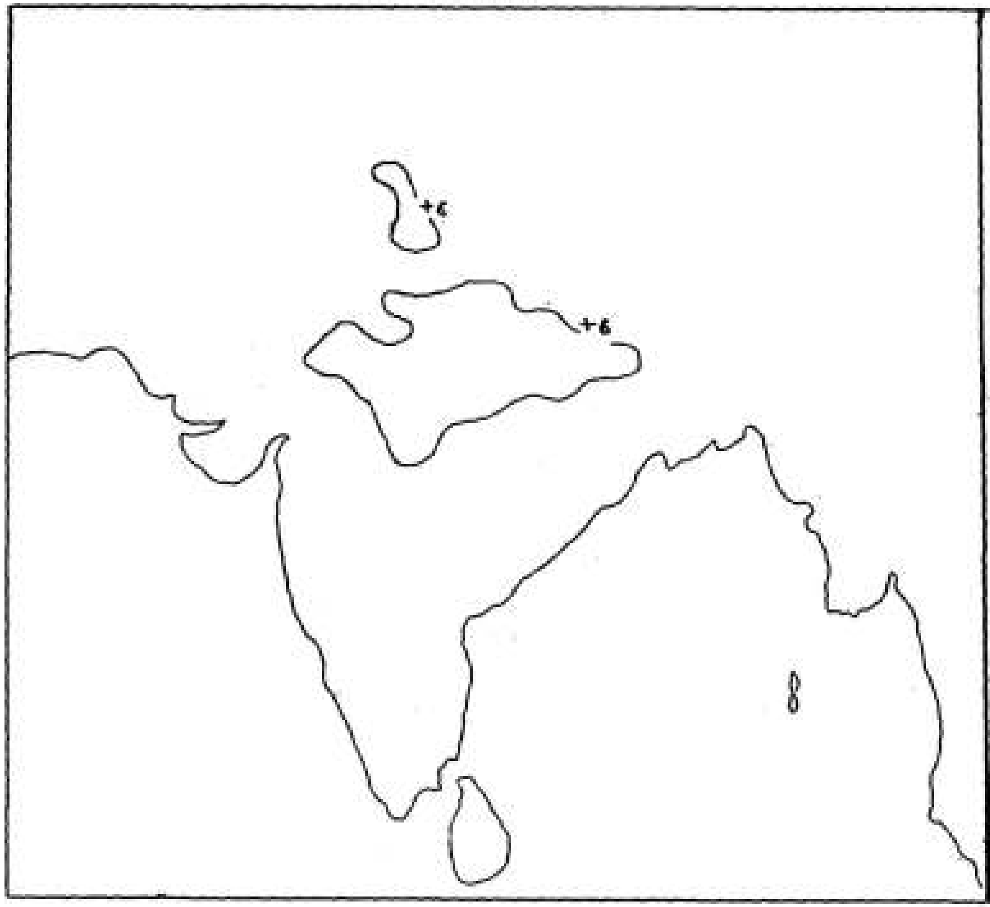
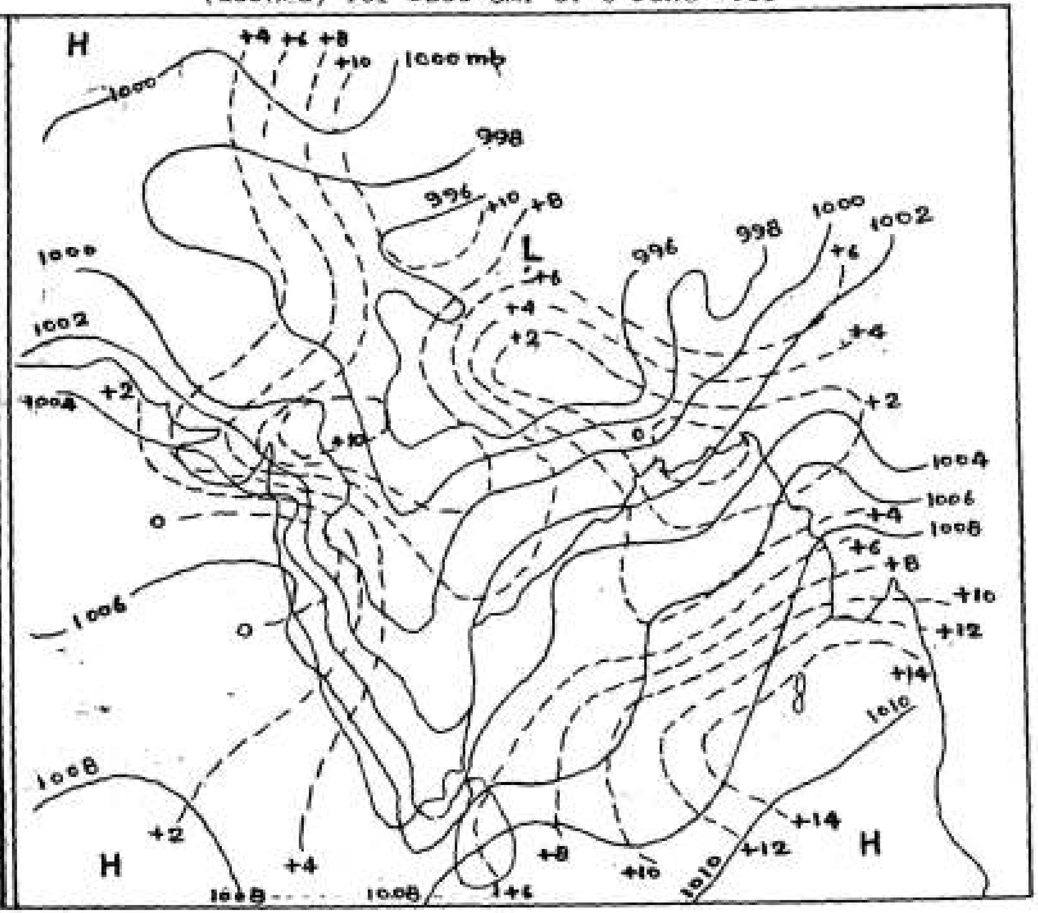


Fig.9(b) : Sea Level Isobars for 1200 GMT of 6 June 1966 and 1000-500 mb departure from normal thickness pattern (dashed) for 1200 GMT of 6 June 1966



Departure from normal thickness values in tens of g.p.m.

Fig.9(c) : 500 mb Contours (continuous lines) and departure from normal (dashed lines) for 1200 GMT of 6 June 1966

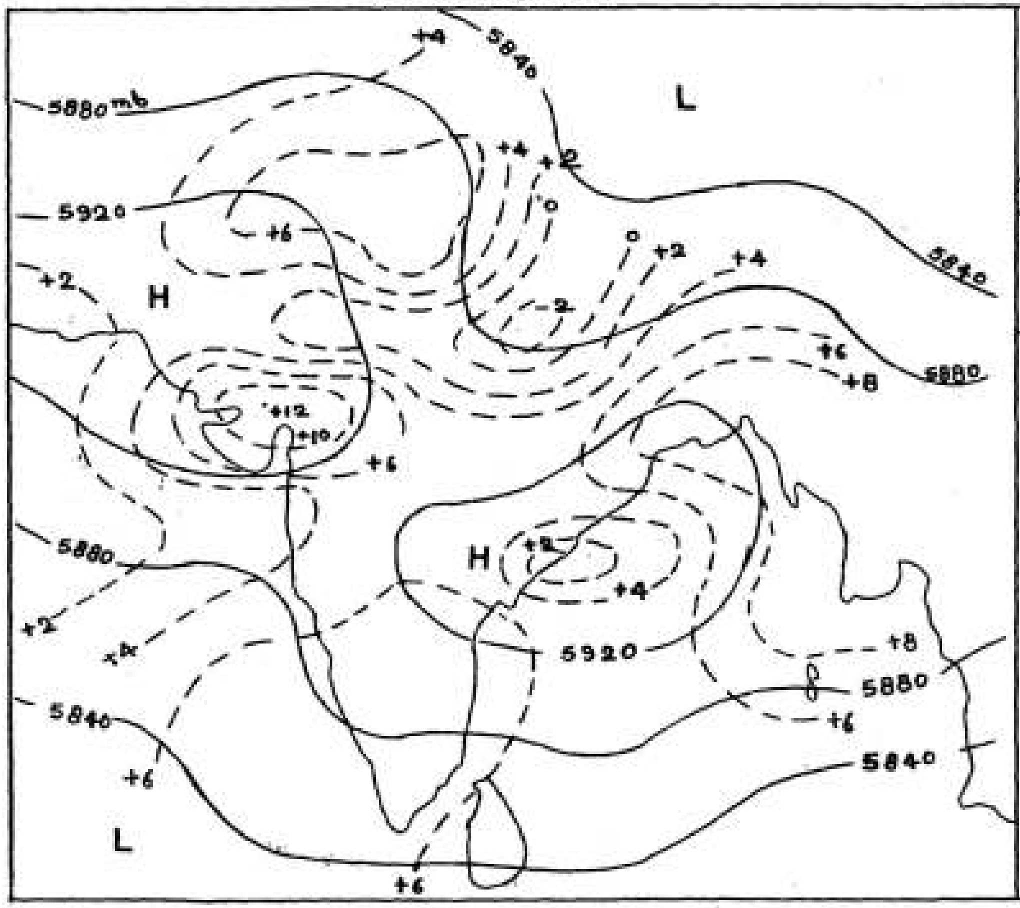
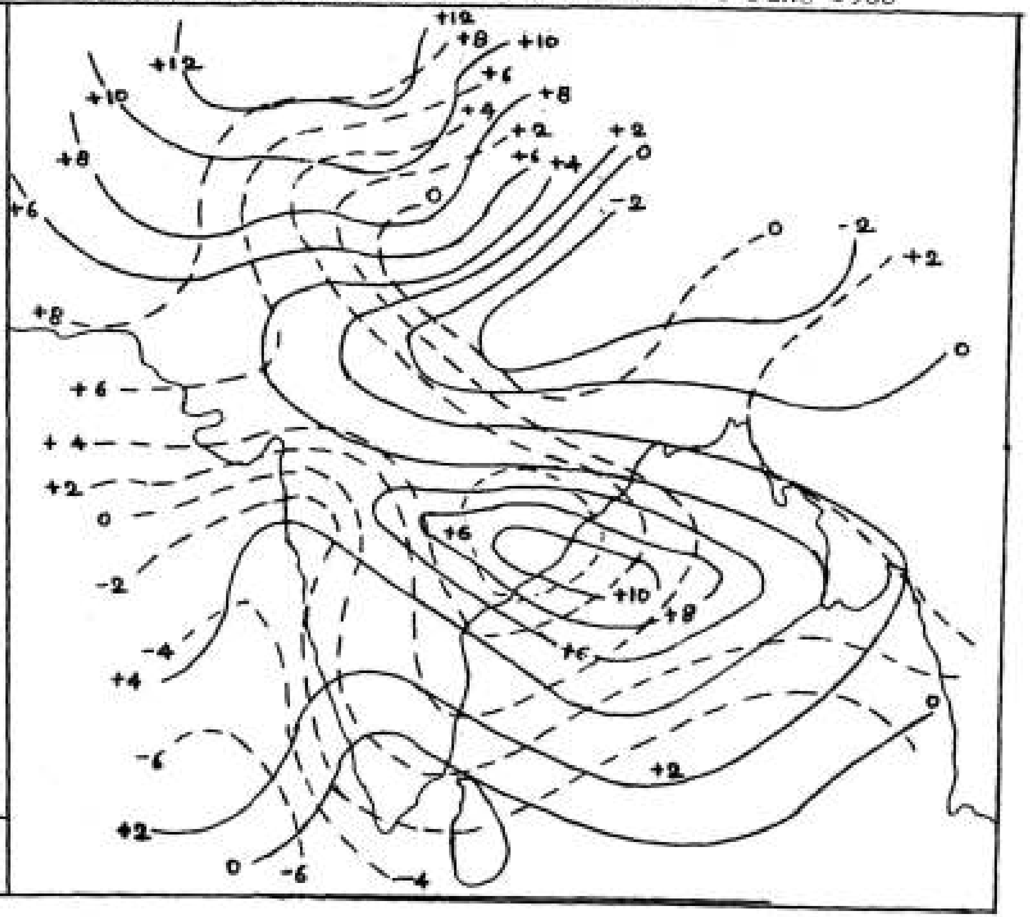


Fig.9(d) : 500 mb 4 day height changes (continuous lines) and 1000-500 mb 4 day thickness changes (dashed lines) chart for 1200 GMT of 2-6 June 1966



(Changes and departures of height values are in tens of g.p.m.)

Fig.10(a) : Area affected by moderate and severe heat wave on 10 June 1966

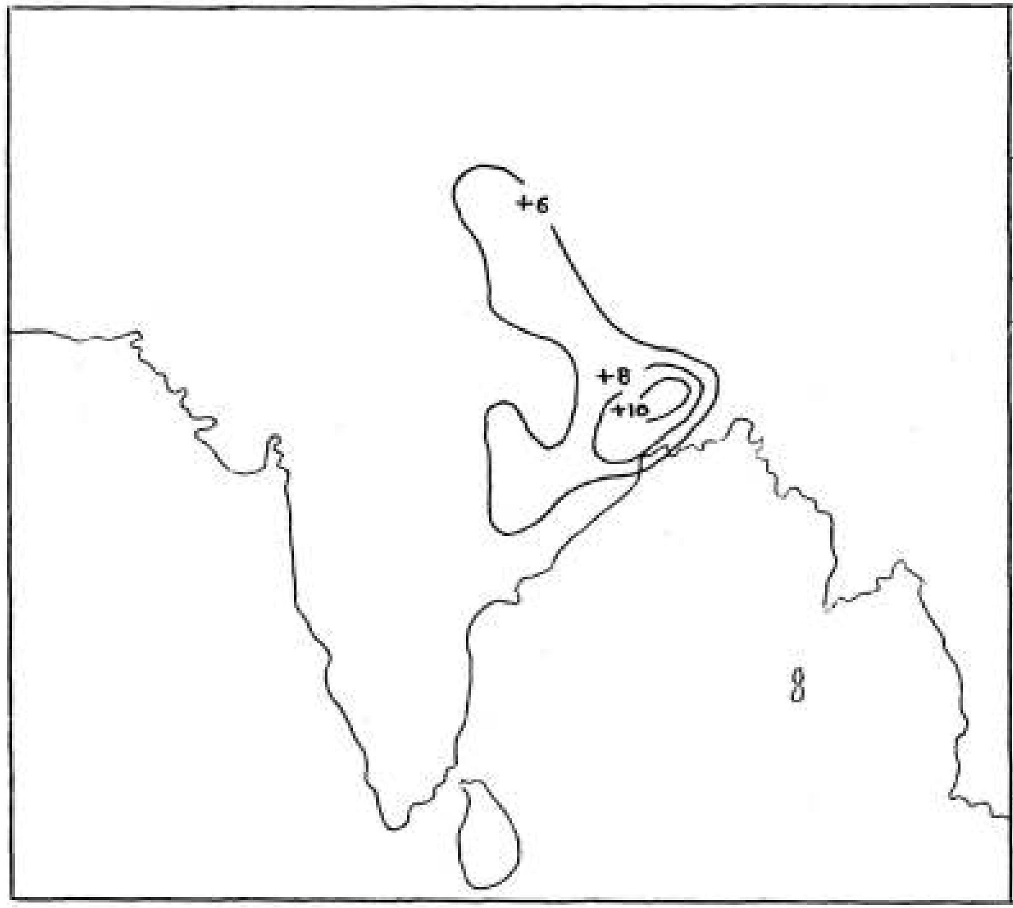
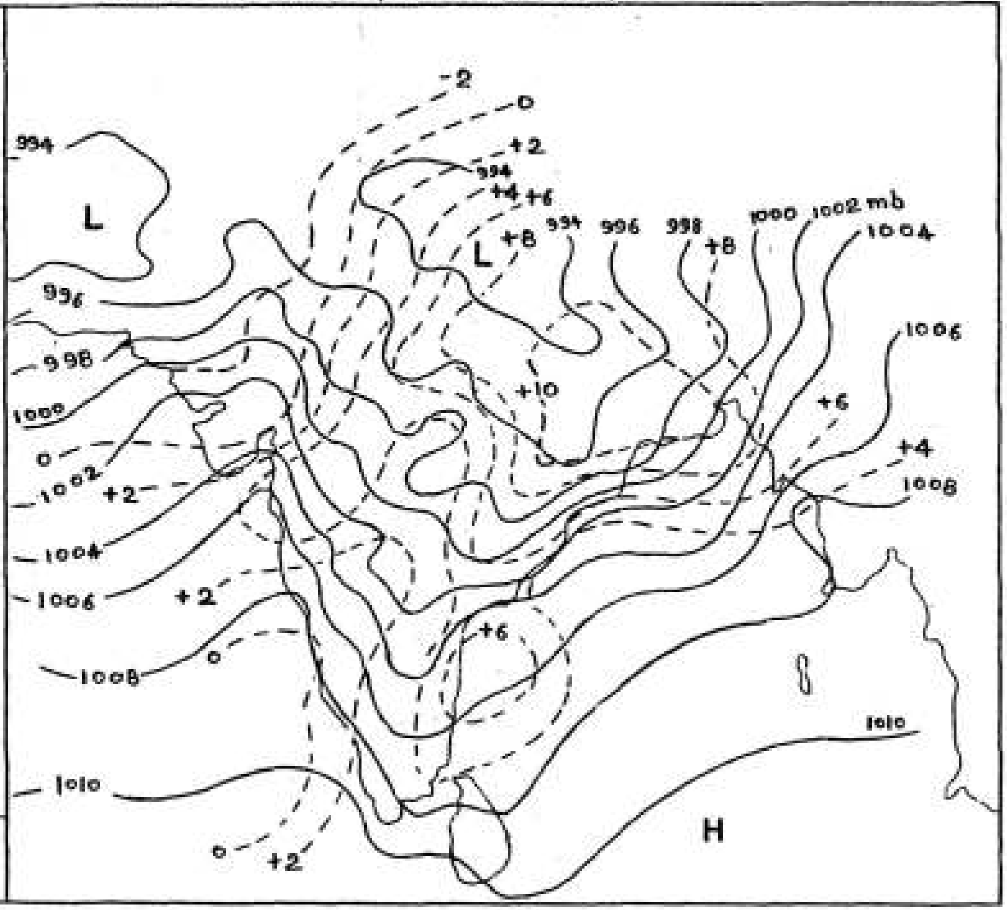


Fig.10(b) : Sea Level Isobars for 1200 GMT of 10 June 1966 and 1000–500 mb departure from normal thickness pattern(dashed)for 1200Z of 10 June'66



Departure from normal thickness values in tens of g.p.m.

Fig.10(c) : 500 mb Contours (continuous lines) and departure from normal (dashed lines) for 1200 GMT of 10 June 1966

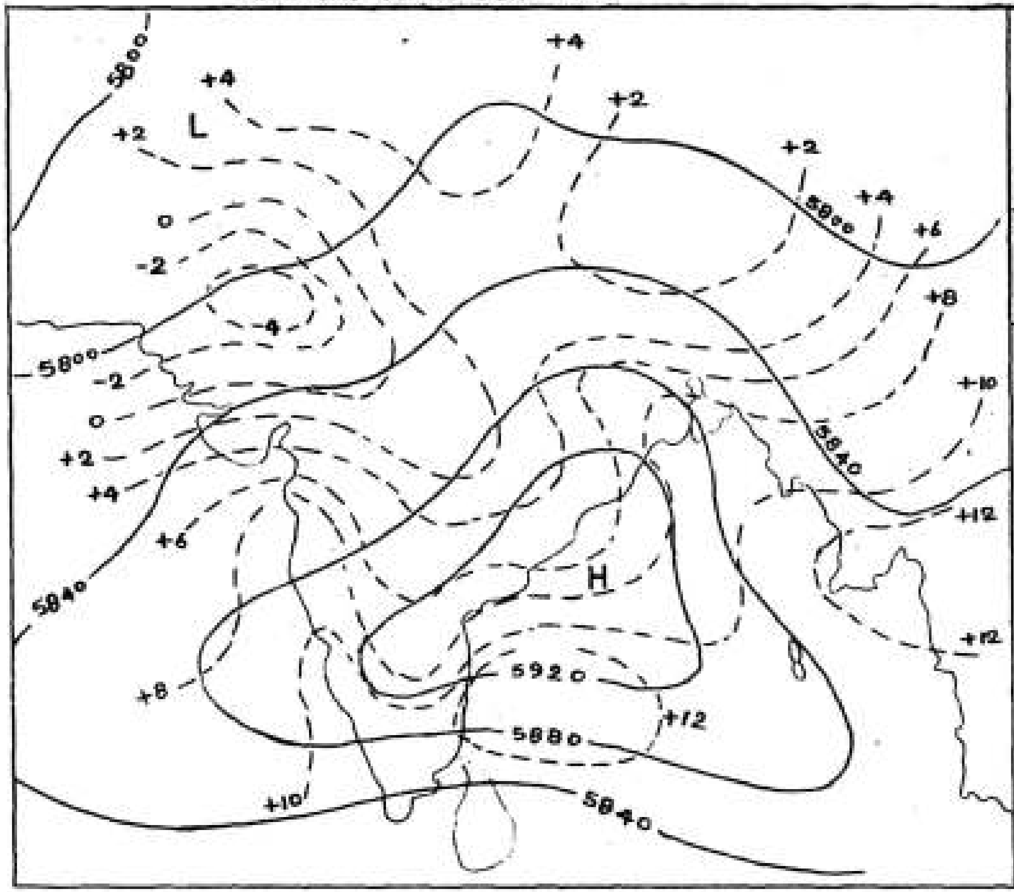
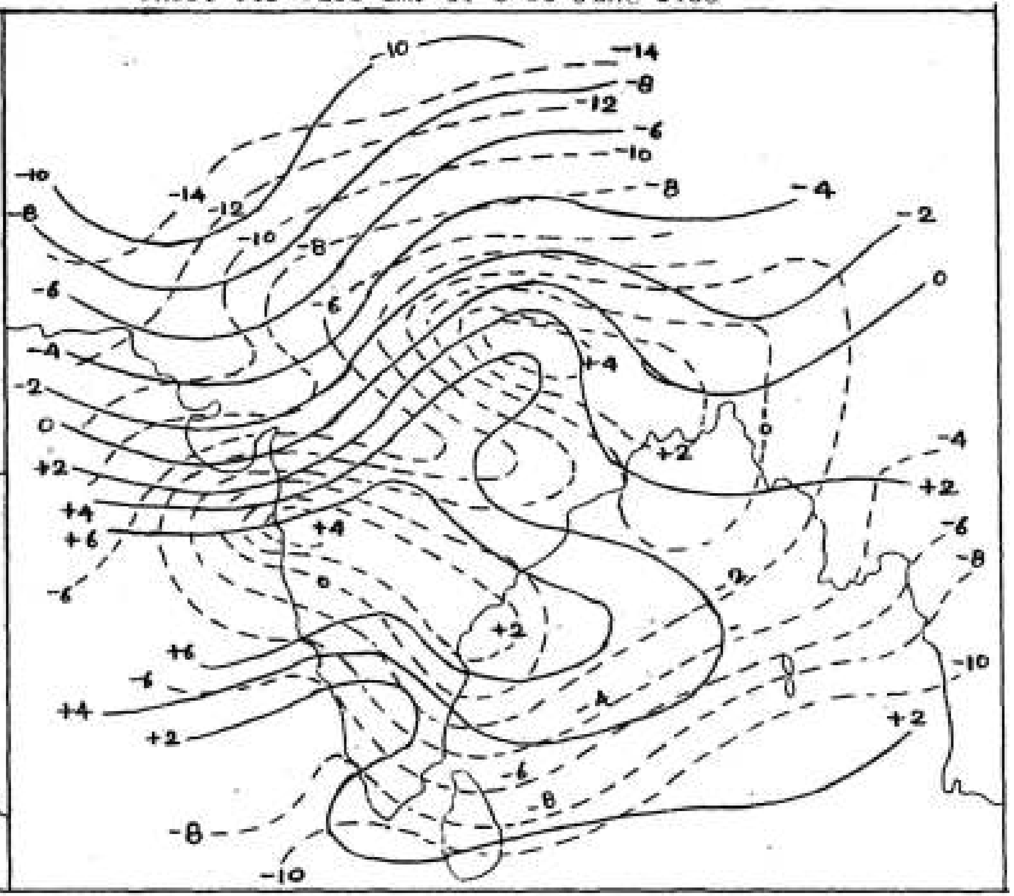


Fig.10(d): 500 mb 4-day height changes (continuous lines). and 1000-500 mb 4-day thickness changes (dashed lines) chart for 1200 GMT of 6-10 June 1966



(Changes and departures of height values are in tens of g.p.m.)

Fig.11(a) : Area affected by moderate and severe heat wave on 12 June 1966

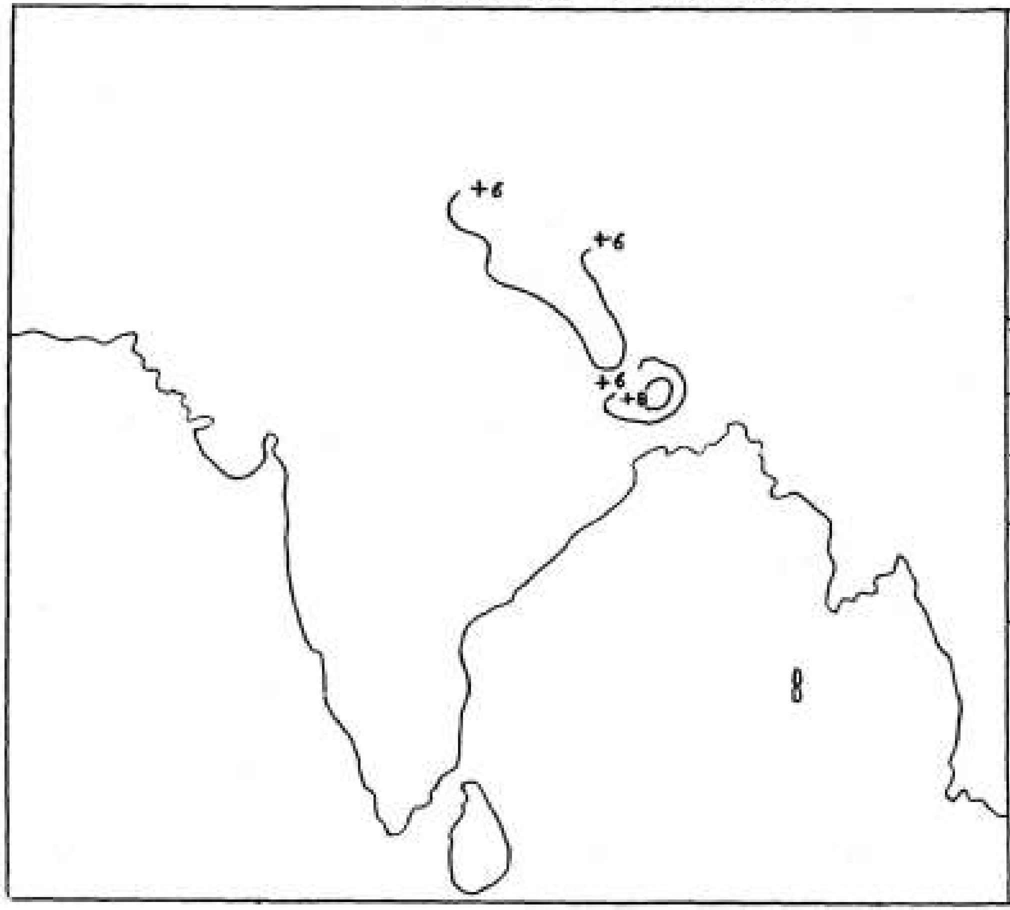
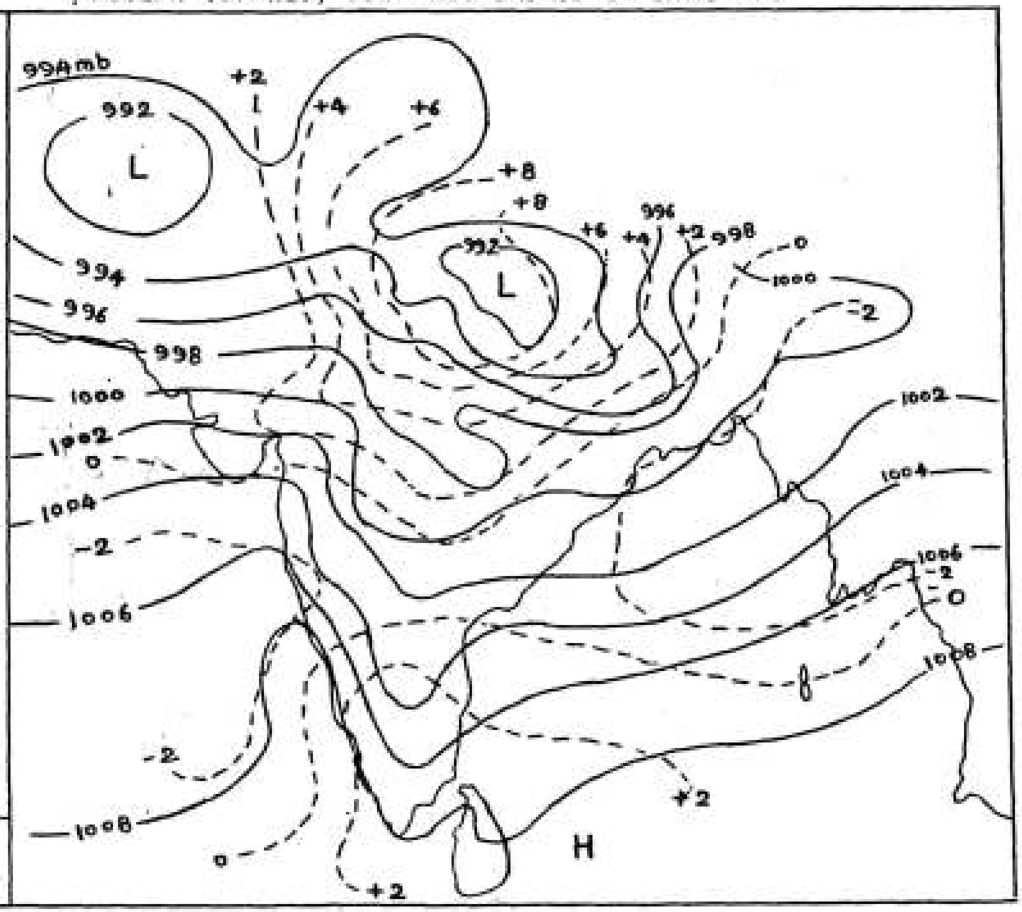


Fig.11(b): Sea Level Isobars for 1200 GMT of 12 June 1966 and 1000–500 mb departure from normal thickness pattern (dashed) for 1200 GMT of 12 June 1966



Departure from normal thickness values in tens of gpm

Fig.11(c) : 500 mb Contours (continuous lines) and departure from normal (dashed lines) for 1200 GMT of 12 June 1966

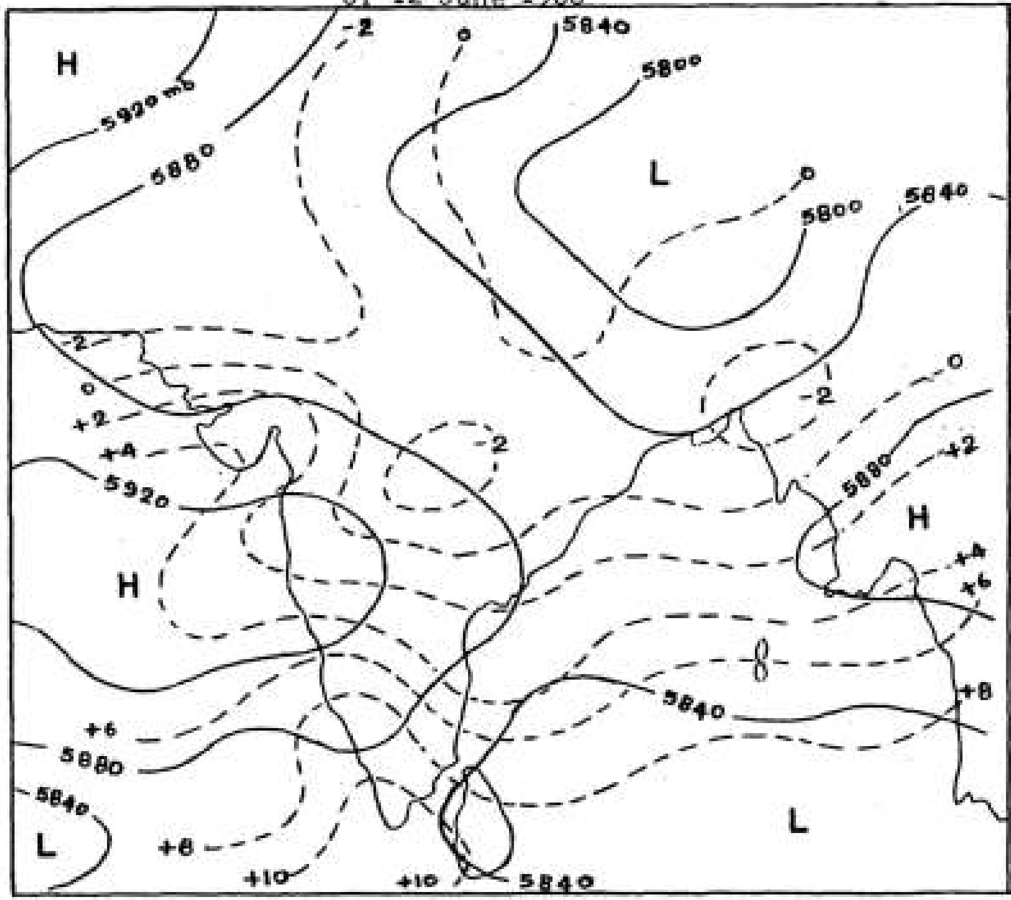
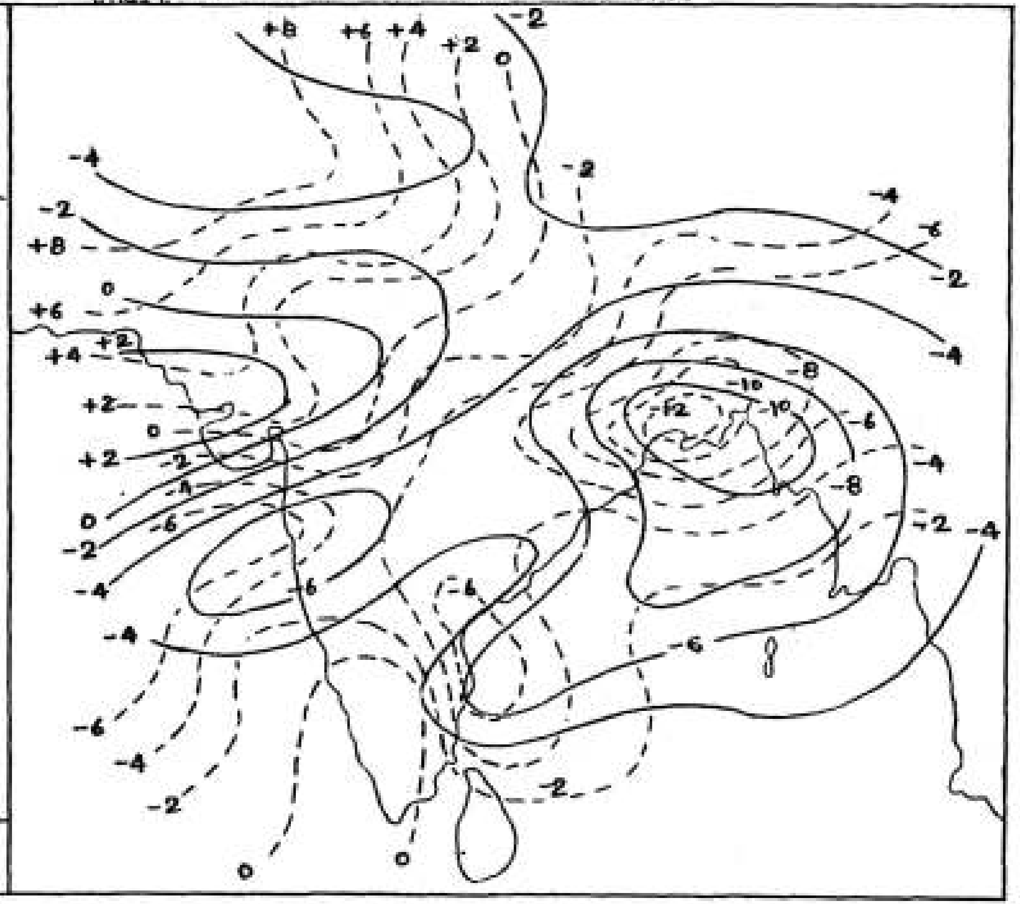
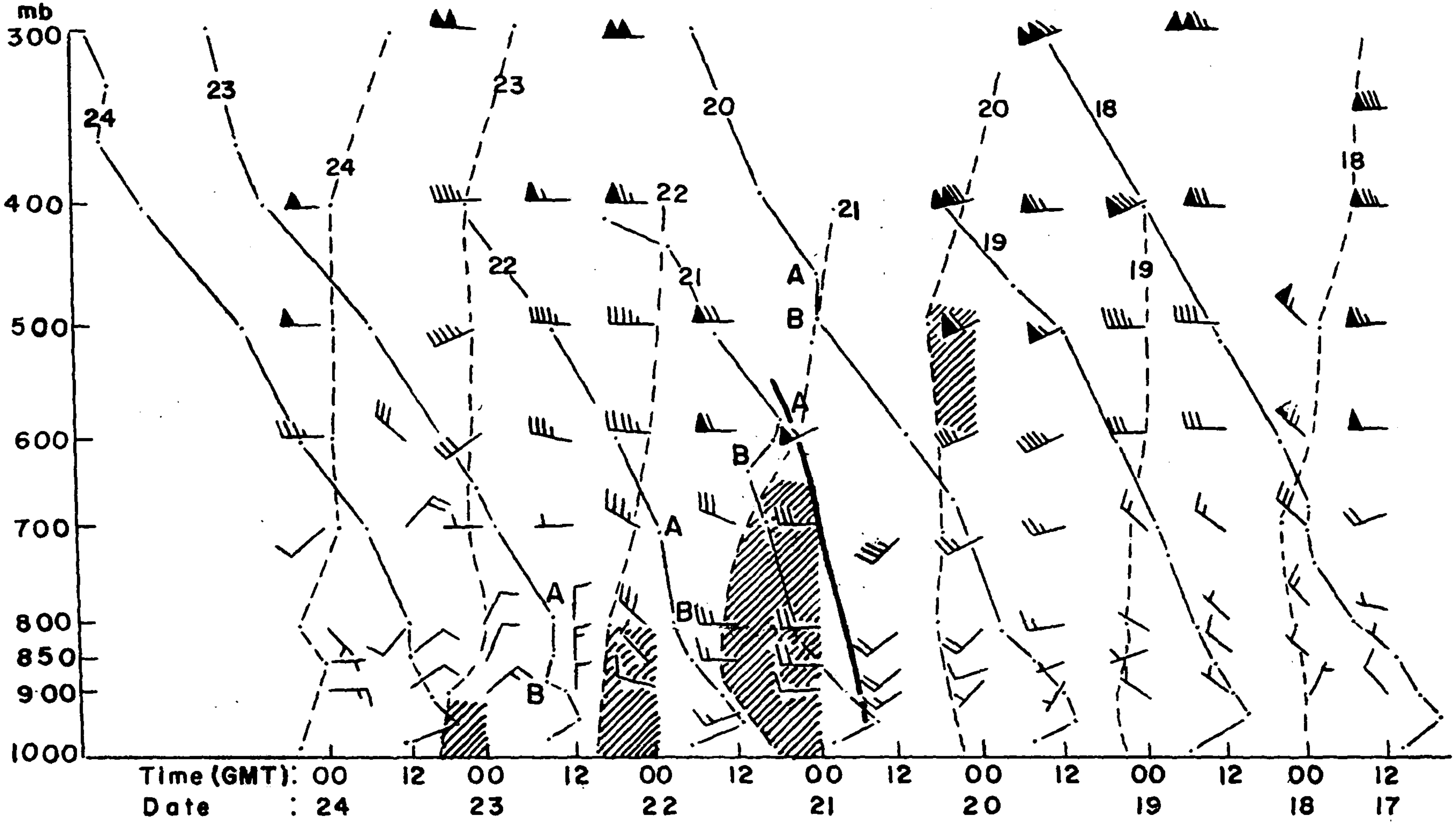


Fig.11(d): 500 mb 2-day height changes (continous lines) and 1000-500 mb 2-day thickness changes (dashed lines) chart for 1200 GMT of 10-12 June 1966



(Changes and departure of height values in tens of gpm)

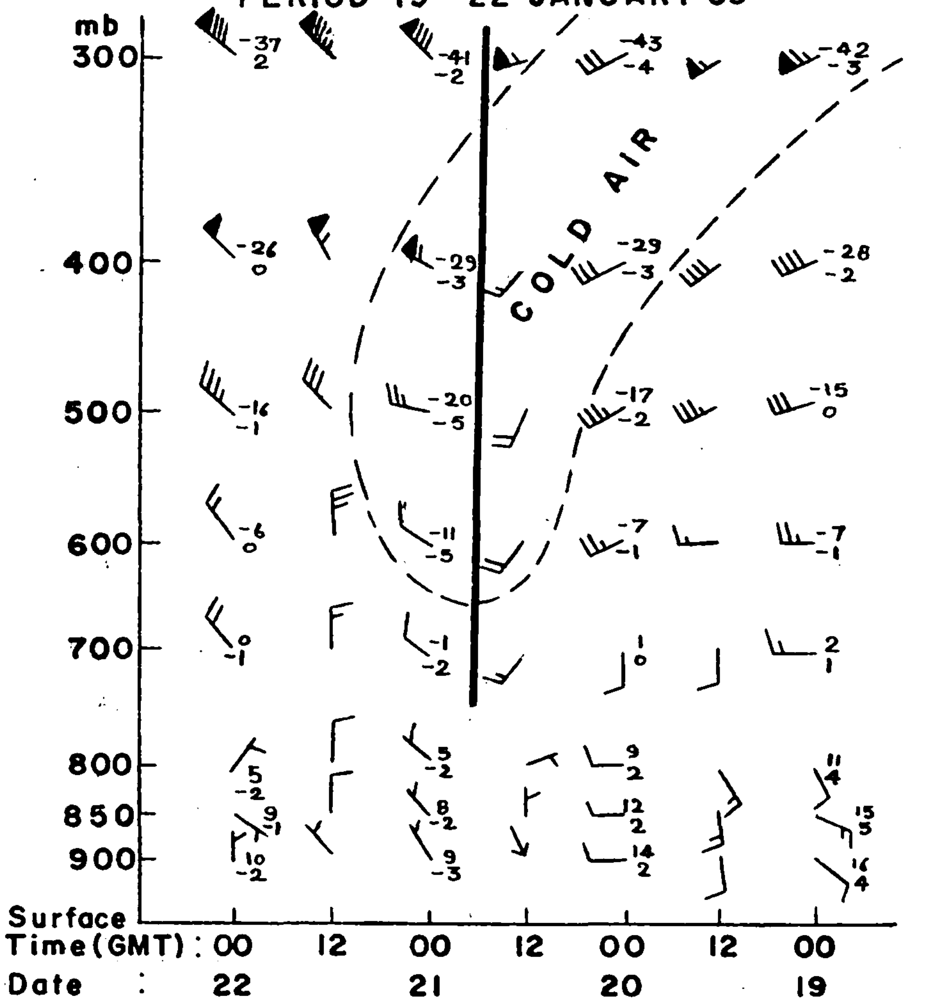
FIG. 12 VERTICAL TIME SECTION OF JODHPUR FOR THE PERIOD ~~19~~ 17-24 JANUARY 1962



Trough line · Vertical Temperature Profile · Temperature Anomaly Profile

Domain of Cold Air (of anomaly -6°c or less) A B: Inversion layer

FIG.13 VERTICAL TIME SECTION OF DELHI FOR THE PERIOD 19-22 JANUARY 59

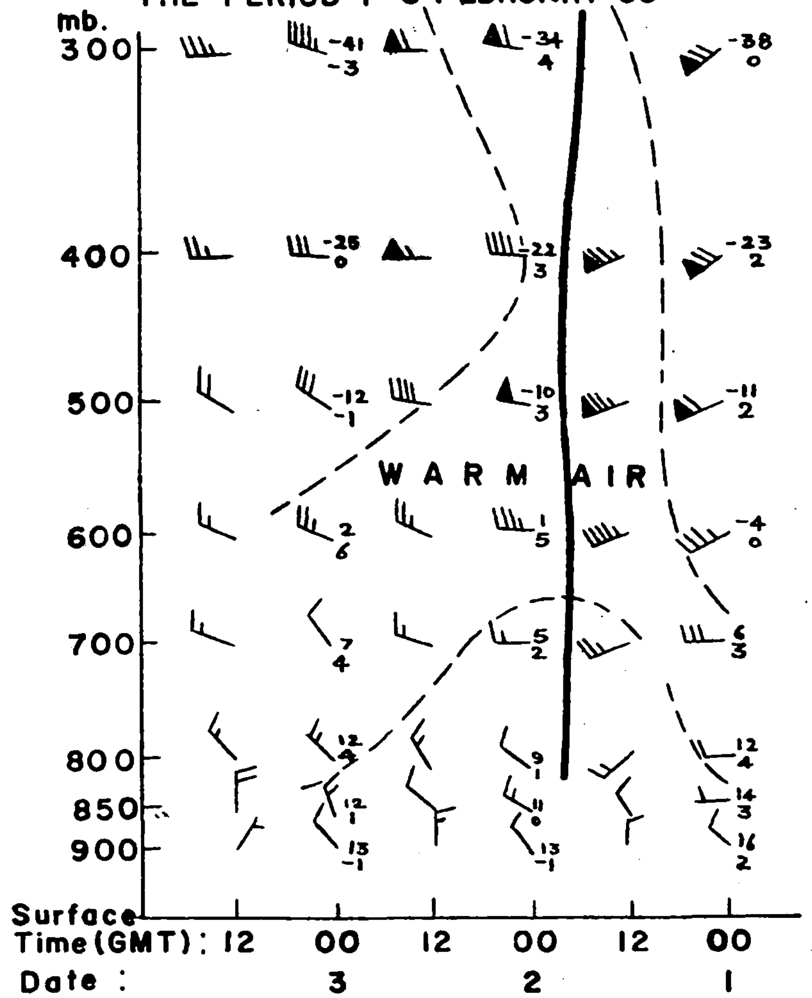


Note: (1) D.B. temperature is plotted on top and its anomaly at the bottom.

(2) Trough line shown by a continuous line.

(3) Domain of cold air (of anomaly −3°C) is shown by dashed line.

FIG.14 VERTICAL TIME SECTION OF JODHPUR FOR THE PERIOD 1-3 FEBRUARY 60



Note: (1) D.B. temperature is plotted on top and its anomaly at the bottom.

(2) Trough line shown by a continuous line.

(3) Domain of warm air (of anomaly +4°C) is shown by dashed line.

FIG. 15 CONTOURS (gpm) AND ISOTHERMS (°C) AT DIFFERENT LEVELS ON 7 FEB. 1961 - 00 GMT

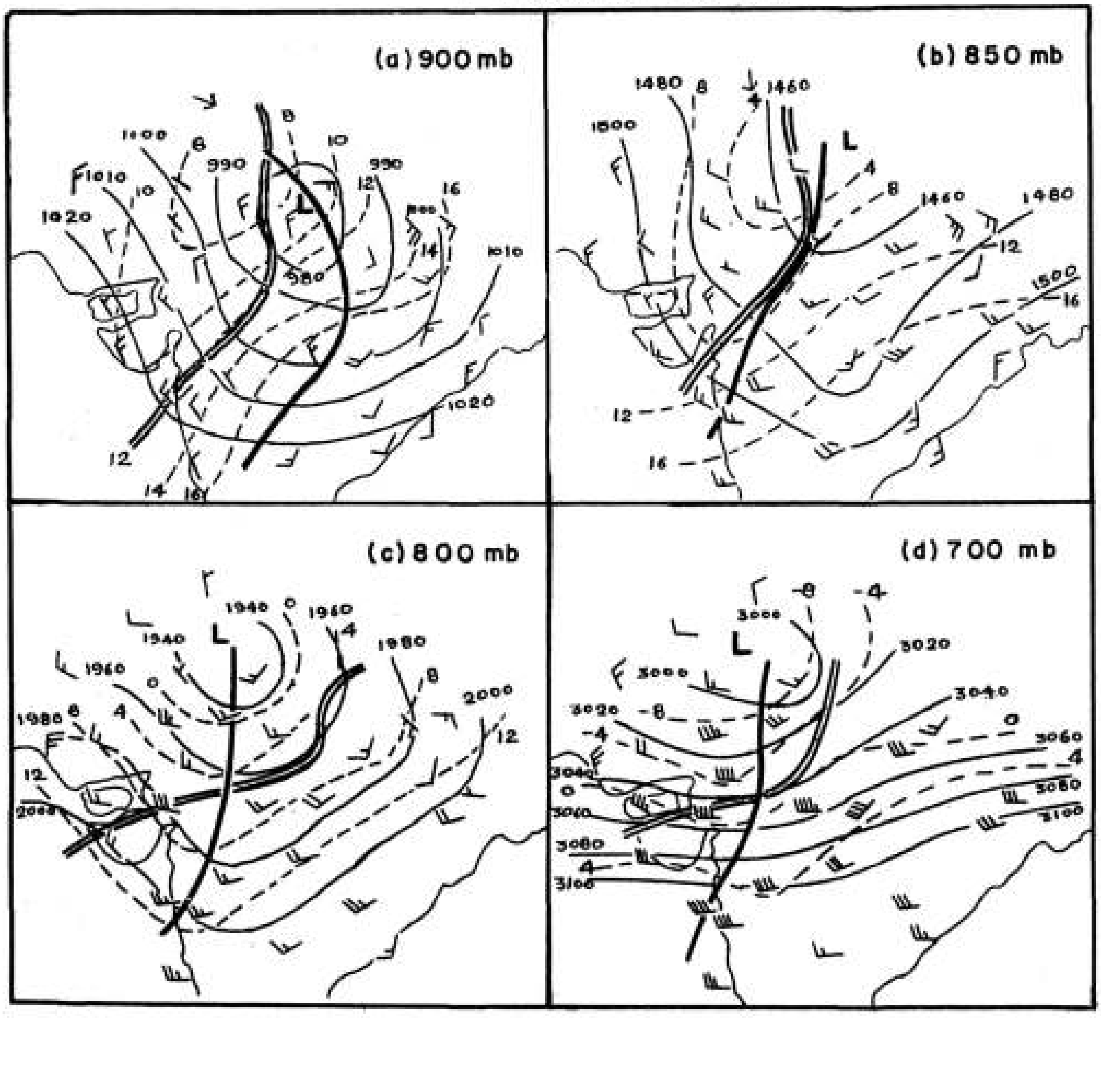
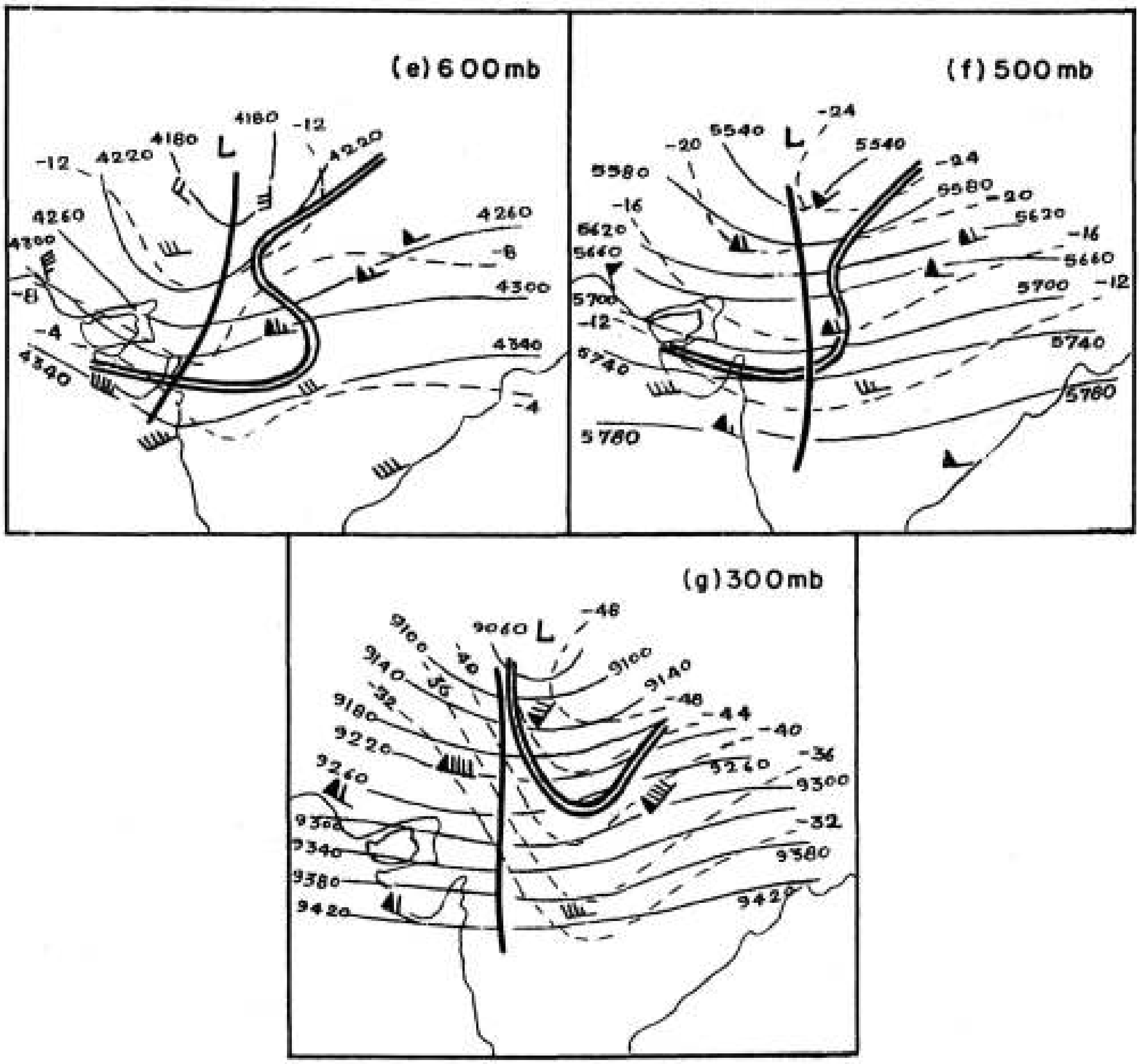


FIG. 15 (contd.)



Contour lines

Isotherms

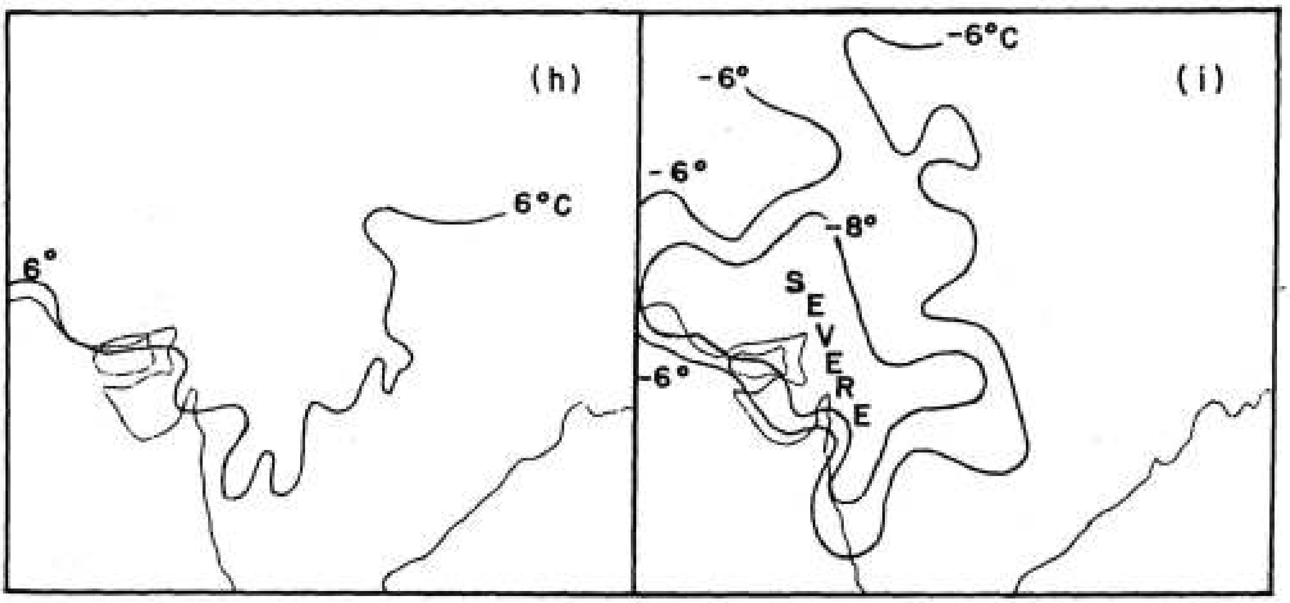
Trough line

Temperature anomaly of −6°C or more

FIG. 15 (Contd.)

Minimum temperature recorded on the morning of 8 February 1961.

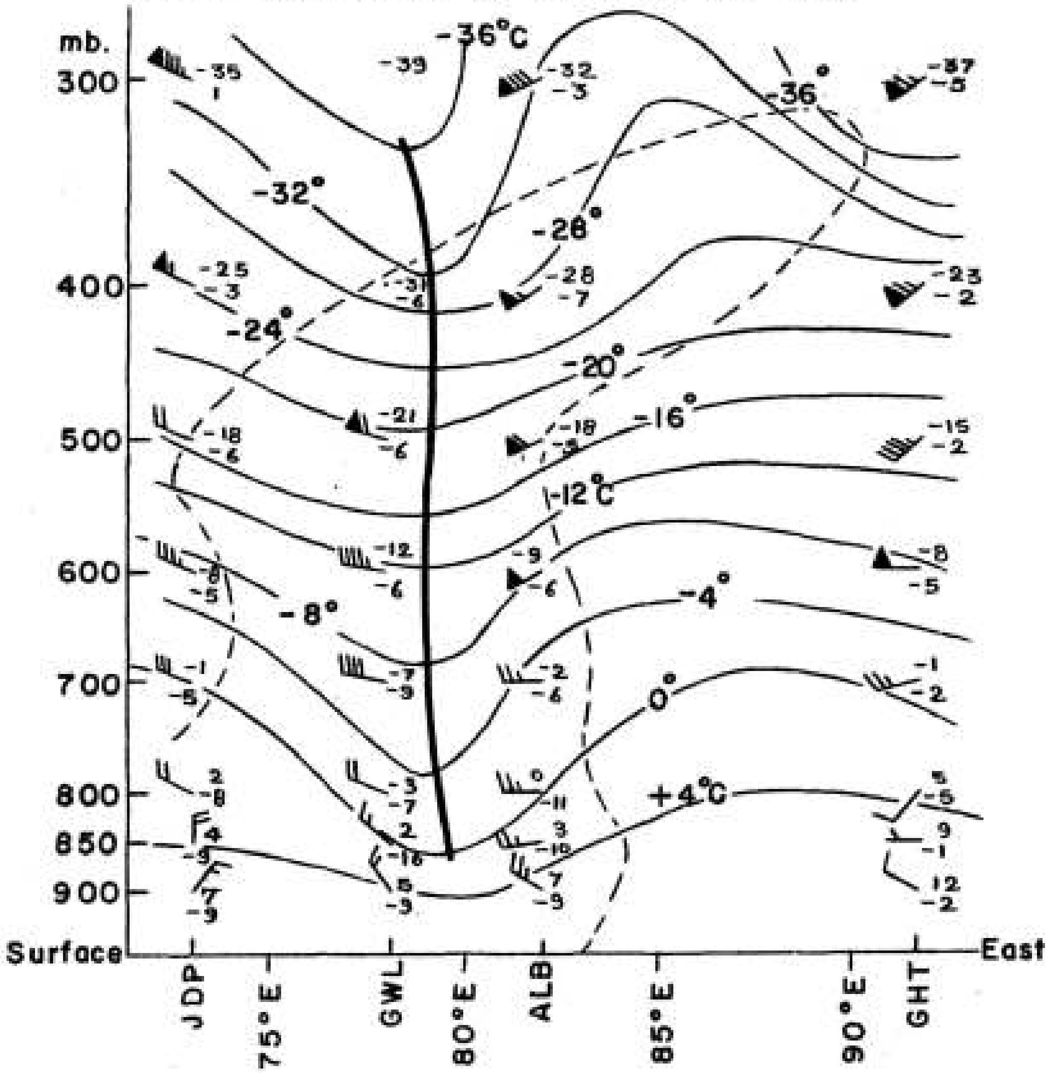
Areas affected by moderate and severe cold wave on the morning of 8 Feb. 1961



Continuous line represents the 6°C isotherm

Continuous line represents the area affected by moderate cold wave — (departure of −6°C) and severe cold wave (departure of −8°C)

FIG. 16 VERTICAL CROSS SECTION (West-East) ALONG LATITUDE 25°N FOR 00 GMT OF 8 FEBRUARY 1961.



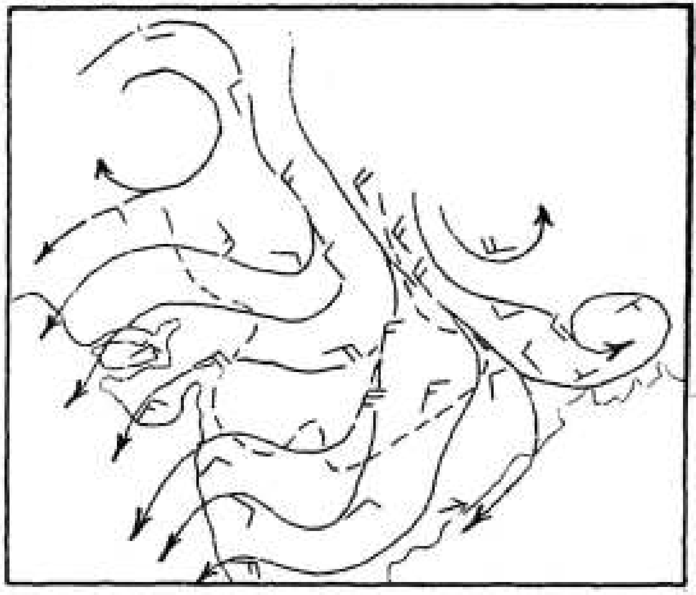
Note: (1) Temperature and its anomaly are plotted at the top and bottom of the respective levels.

(2) Thin continuous lines are isotherms at 4°C intervals.

(3) Dashed lines represent the domain of cold air (of anomaly -6°C)

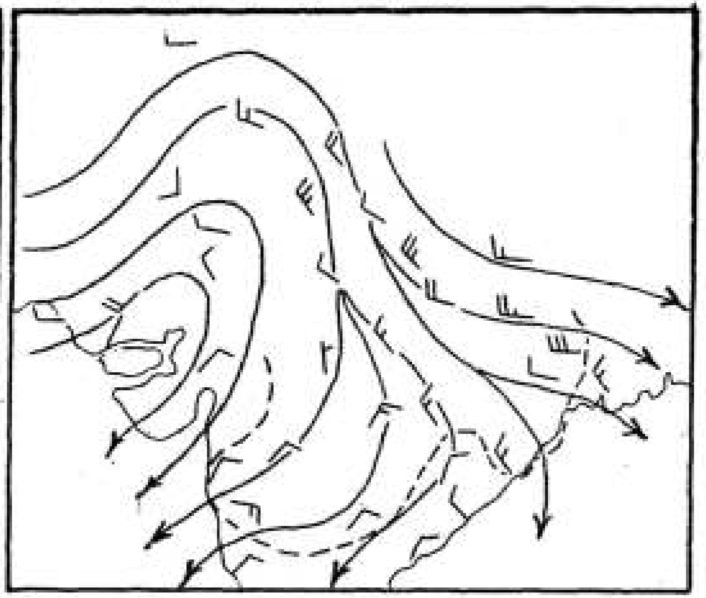
(4) ——— Trough line.

Fig.17(a) Flow pattern at 600 m.a.s.l. at 0230 GMT of 23 Jan. 53



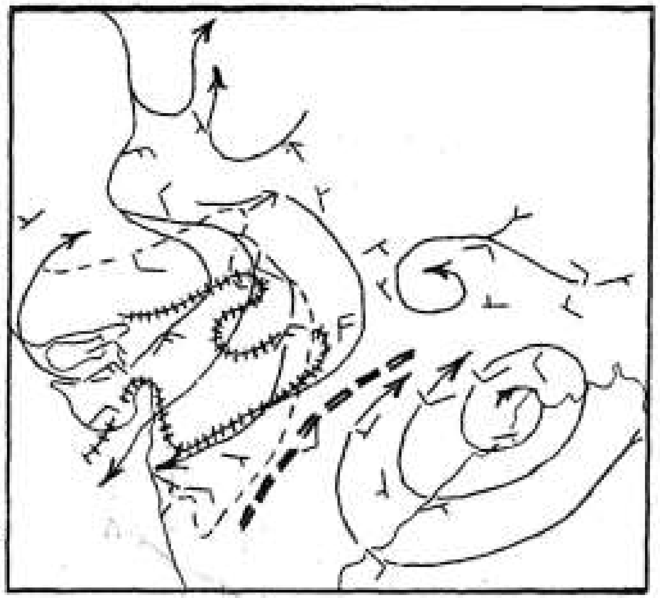
Area affected by surface cold wave on 24 January 1953 shown by dashed line.

Fig.17 (b) Flow pattern at 900 m.a.s.l. at 0230 GMT of 24 Jan. 53



Area affected by cold wave on 25 Jan. '53 shown by dashed line.(Note the southern boundary of the surface cold wave area has shifted further to the south).

Fig. 18 Flow pattern at 900 m.a.s.l. at 00 GMT of 22 Jan. 62



- - - - - Boundary of surface cold wave area on 22nd morning.

+++++++ Boundary of surface cold wave area on 23rd morning.

= = = = Discontinuity line.

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