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The role of Himalayan Massif-Tibetan Plateau and the mid-tropospheric sub-tropical ridge over north India during the advance phase of the southwest monsoon

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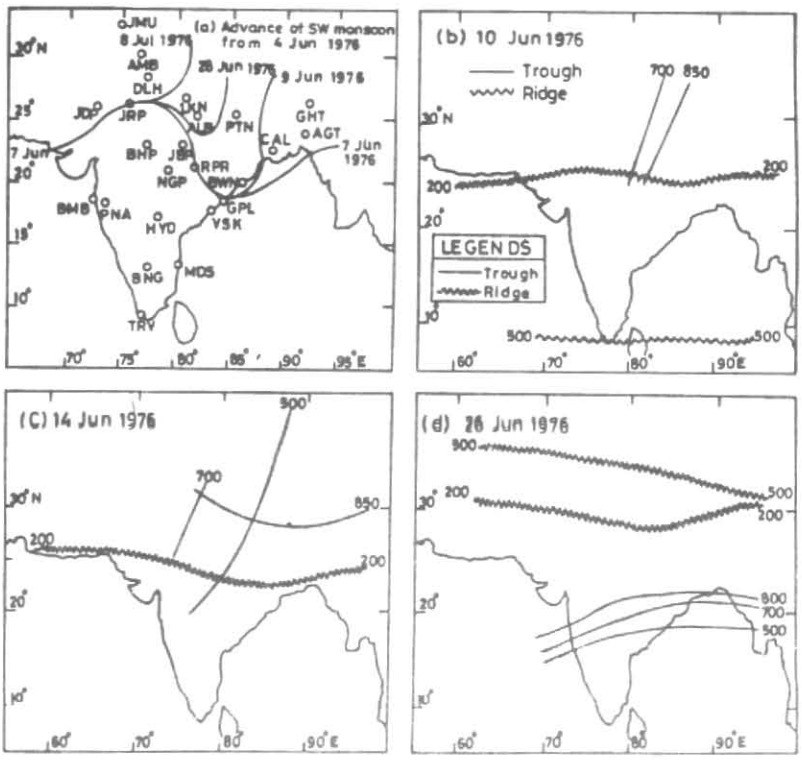
सार— भारतीय उपमहाद्वीप में मानसून निरंतर गति से आगे नहीं बढ़ता है। मानसून यहाँ रूक-रूक कर आगे बढ़ता है। बहुत से आँकड़ों के नमूनों से यह पता चला है कि मानसून की गति प्रायः उत्तरी पश्चिमी भारत, गुजरात, उत्तरी पश्चिमी मध्य प्रदेश और पश्चिमी उत्तर प्रदेश की बाहरी सीमा पर लम्बी अवधि के लिए अवरुद्ध हो जाती है जिसके कारण इन क्षेत्रों में मानसून के पहुँचने में पर्याप्त विलम्ब होता है। इतनी दीर्घ अवधि तक मानसून के अवरुद्ध रहने के कारण का पता उत्तर भारत में किसी सिनॉप्टिक प्रवलन अनुमाप के अभाव की स्थिति में; पश्चिमी हिमालय तिब्बत पठार के मध्य क्षोभमंडलीय पश्चिमी प्रवाह में यांत्रिक प्रबलन से लगाया जा सकता है। 1976, 1982 और 1991 के दौरान उत्तरी पश्चिमी भारत और समीपवर्ती क्षेत्रों में दक्षिणी पश्चिमी मानसून लम्बे समय तक अवरुद्ध रहा और यही स्थिति 1985 में जून-जुलाई के दौरान उत्तरी कोंकण में थी। उन वर्षों में, मानसून के आगमन की आरम्भिक अवस्था के दौरान भारत के मध्य क्षोभमंडल में उपोष्ण रिज (एस टी आर) की स्थिति या तो कमजोर थी अथवा यह अस्तित्व में ही नहीं थी। उपोष्ण रिज (एस टी आर) के न होने से, मध्य क्षोभमंडलीय स्तरों में पश्चिमी द्रोणी की गतिविधियों का विस्तार दक्षिणी अक्षांश तक था जिसके कारण मानसून की गति अवरुद्ध रहने से यह लम्बे समय तक वहाँ नहीं पहुँचा। 1995 में मानसून के लम्बे समय तक अवरुद्ध रहने के दौरान किए गए परीक्षण अध्ययन से इस तथ्य की पुष्टि हुई है। दूसरी तरफ, वर्ष 1990 में, उत्तरी भारत में जून माह के बीच में मध्य क्षोभमंडलीय उपोष्ण रिज (एस टी आर) की स्थिति स्पष्ट थी जो पश्चिमी द्रोणी का दक्षिणीभिमुखी विस्तार रोकने में सहायक हुई। परिणामस्वरूप भूमध्यरेखीय द्रोणी सुव्यवस्थित रही और इसके धीरे-धीरे उत्तरी भारत की ओर खिसकने से समूचे देश में दक्षिणी पश्चिमी मानसून बिना किसी उल्लेखनीय रूकावट के शनैः शनैः आगे बढ़ा।

ABSTRACT. The advance of monsoon over the Indian sub-continent is not a continuous process. It advances in a phased manner. It has been observed from large sample of the data that the monsoon current often stagnates outside northwest India. Gujarat, northwest Madhya Pradesh and west Uttar Pradesh for a long period resulting in delaying its advance considerbaly over these areas. The cause of such prolonged stagnation can be identified to the mechanical forcing of the western Himalayas-Tibetan plateau on the mid-tropospheric westerly flow in absence of any synoptic scale forcing over north India. During 1976, 1982 and 1991 there was prolonged stagnation of southwest monsoon over northwest India and neighbouring areas and, in 1985, it was over north Konkan during June-July. In those years, the sub-tropical ridge (STR) in the middle troposphere over India was weak or absent during the initial phase of advance of monsoon. In absence of the STR, the westerly trough activity in the mid-tropospheric levels extended to southern latitude disrupting the monsoon flow and bringing prolonged stagnation. The observation was confirmed on a test study conducted during the prolonged stagnation of the monsoon of 1995. On the other hand, in the year 1990, the mid- tropospheric STR became prominent from middle of June over north India and it helped in restricting southward extension of westerly troughs. Consequently the equatorial trough remained organised, shifted gradually over north India and caused the gradual advance of SW monsoon over the entire country without considerable stalling.

Key words— Stagnation, ENSO, Weekly circulation anomaly, Equatorial trough (ET), Sub-tropical ridge (STR).

1. Introduction

Monsoon onset over Kerala has been studied both from the planetary scale and regional scale aspects by many. Eliot (1886) linked it to the establishment of the low level flow across the equator into the Arabian Sea and the Bay of Bengal. Yin (1949) linked the onset with the major shift in



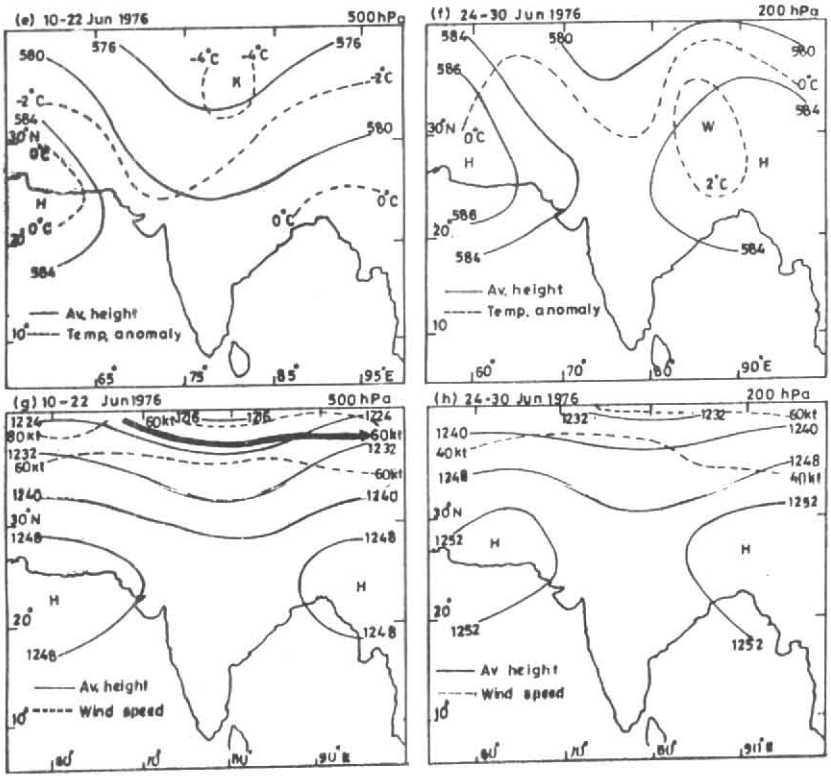
Figs.1(a-d). (a) Advance of SW monsoon, 1976 from 7 June onwards and (b-d) Locations of troughs and ridge at different levels (hPa) on 10, 14 and 26 June 1976

the zonal circulation in the northern hemisphere, when the sub-tropical jet (STJ) shifts northward across Himalayas. Flohn (1960) linked the phenomenon with the establishment of heat source over Tibet and Ananthakrishnan (1977) with the downward and upward shift of the upper and lower troposphere features respectively under the seasonal heating influence. Data collected under the MONEX experiments added to the information base. The onset event has been linked with the building up of available potential energy (APE) in the planetary scale, its conversion into eddy kinetic energy (EKE) on the planetary and regional scales in the upper and middle tropospheres and the sudden increase of the mean kinetic energy (MKE) of lower troposphere flow over north Indian Ocean (Krishnamurti and Ramanthan 1982) and building up of the moisture layer over the Indian seas (Pearce and Mohanty 1984).

Whereas the onset of Indian summer monsoon (ISM) over Kerala is of importance, the advance of monsoon over different parts of the country is also equally important. The advance is not a continuous affair but occurs in pulses. There are years, when a hiatus occurs and the northward or the westward propagation of the monsoon is arrested. Most of the years there are only short lulls of 7-10 days, but there are years when this stalling of the advance of monsoon continues for over 2 weeks period. Ramasastry *et al.* (1986) recognised it. Biswas *et al.*, (1989) and Deshpande *et al.* (1991) brought out some features about it. Subbaramayya and Bhanukumar (1978) studied monsoon rain spells at a station in relation to westward moving synoptic and sub-synoptic scale systems and emphasised the stagnation in the monsoon over preferred regions. Detailed study is needed to understand the mechanism of unusual hiatus in the advance of monsoon. The present study is an attempt in this direction.

2. Data and methodology

Data on advance of the monsoon for the period from 1960 to 1993 have been collected from the Annual Monsoon Summary published by the India Meteorological Department (IMD) and Indian Summer Monsoon Weather Summary published in Mausam. Periods of stagnation have been worked out from the above data. For the case studies of stagnation, daily weather charts of Weather Central Office Pune, have been consulted. The position of troughs and ridges at 850, 700, 300 and 200 hPa levels for each day beginning from the date of onset over Kerala to advance over the entire country for the year 1976, 1982, 1985, 1990, 1991 and 1995 have been marked from those weather charts for



Figs.1(e-h). (e & f) 500hPa average height (gpm)X10 and temperature anomaly (°C) and (g & h) 200 hPa averaged height (gpm)X10 and wind speed (kt)

the study of their impact on the advance of the southwest monsoon over the country. For preparation of the mean charts presented here, grid point contour heights (gpm), temperatures (°C) and winds (kt) have been interpolated from the analysed charts of the Indian Ocean and Southern Hemisphere Analysis Centre, (INOSHAC) Pune. Normals of upper air temperatures at grid points are collected from the normal charts and data published by IMD. Temperature anomalies at 500 hPa level at grid points are thus computed from these set of data. Besides, the weekly circulation anomaly charts have also been consulted for the study of the anomaly winds. The charts presented in this paper have been constructed from the above mentioned data.

The authors have studied in detail 4 cases of prolonged stagnation of one or both the branches of monsoon (1976, 1982, 1985 and 1991) and a case (1990), where the monsoon advanced over the country without any prolonged stagnation. From the study it appears that the mechanical forcing due to Himalayan ranges-elevated Tibetan Plateau and the synoptic forcing are two important parameters which play key roles in prolonged stagnation or otherwise. Koteswaram (1958) has stressed the role of Tibetan high in anchoring the tropical easterly jet (TEJ) which is a component of the monsoon system. Hahn and Manabe (1975) has provided numerical simulation of the monsoon with and without Himalayas to focus the role of these barriers on the monsoon.

3. Case studies

Out of the 12 cases of prolonged stagnation (> 15 days) shown in Table 1, four case studies of stagnation (> 15 days) and one, when there was no such stagnation, are presented here. During the years 1976, 1982 and 1991 there was stagnation of the advance of both the Arabian Sea and the Bay of Bengal branches of monsoon over India for more than 15 days. In the year 1985 the Arabian Sea branch of the monsoon current stagnated over north Konkan for more than 30 days but the westward advance of the monsoon over the Gangetic valley and neighbourhood continued without any prolonged stagnation. The fifth case study is of the year 1990, when the monsoon advanced over the country without much halting over any particular area. The sixth case of prolonged stagnation during 1995 is a test study. The analysis was in fact, done for all the cases but as the results are similar, other cases are not discussed in detail to save space.

TABLE 1
Details of prolonged stagnation (15 days) of southwest monsoon (1960 - 1993)

Year	Arabian Sea Branch		Year	Bay of Bengal Branch	
	Period/Days	Area of stagnation		Period/Days	Area of stagnation
1960	24 May-12 June (20)	South of Lat. 15°N	1960	2-17 June (16)	East of Long.90°E
1965	17 June-2 July (16)	South of Gujarat *i.e.*, over North Konkan			
1968	18 June-4 July (17)	South of Lat. 21°N	1968	18 Jun-4 July (17)	East of Long.83°E
1969	8 June-11 July (34)	South of Lat. 21°N	1969	7-30 June (24)	East of Long.83°E
1971	9-25 June (17)	South of Lat. 24°N			
1974	8-27 June (20)	South Konkan & Goa coast			
1976	4-30 June (27)	South of Lat. 21°N	1976	10-27 June (18)	East of Long.89°E
1980	7-22 June (16)	South of Lat. 20°N			
1982	18 June-11 July (24)	South of Lat. 21°N	1982	16 June-13 July (28)	East of Long. 84°E
1985	8 June-13 July (36)	South of Lat. 20°N			
1987	14 June-13 July (30)	South of Lat.23°N	1987	9 June-4 July (26)	East of Long. 85°E
1991	11 June-11 July (30)	South of Lat.22°N	1991	13 June-10 July (27)	East of Long.79°E

3.1. *Cases of prolonged stagnation of both the branches (Arabian Sea and Bay of Bengal) of the monsoon*

3.1.1. *Stagnation of monsoon (10-27 June, i.e., 18 days) during 1976*

During the year 1976, the advance of monsoon was arrested from 10 to 27 June outside Orissa, Bihar, Uttar Pradesh and NW India. The advance of the SW monsoon, 1976 from 7 June onwards has been shown in Fig.1(a).

Locations of the troughs and ridges at 850, 700, 500 and 200 hPa levels during the initial stage of the stagnation (10 and 14 June) and just prior to the commencement of further advance (26 June) have been shown in Figs.1(b-d).

The dominant synoptic features during the stagnation period were the advent of mid-tropospheric westerly troughs in the Indian latitudes and their amplification to the south of the Tibetan Plateau in absence of the sub-tropical ridge (STR) at that level over north India and adjoining Tibetan Plateau.

On 10 June, a trough in the mid-tropospheric westerlies (500 hPa) appeared over north Pakistan [Fig.1(b)]. The mid-tropospheric STR ran along Lat. 9°N while in the upper troposphere (200 hPa) it ran along Lat. 25°N across the country. During its passage to the east, the trough amplified to the south of the Tibetan Plateau and ran from Bihar Plains to Marathwada on 14 June [Fig.1(c)]. Another mid- tropospheric westerly trough appeared over north Pakistan on 15 June. It also amplified to the south of the plateau by next day and gradually moved away eastwards. Consequent to the passage of those mid tropospheric westerly troughs across the sub-continent, the northern hemispheric equatorial trough, henceforth referred to as equatorial trough (ET) in the lowest troposphere was disorganised.

The mid -tropospheric STR developed over north India running through Alibag in the west to Agartala in the east on 22 June. A westerly trough in the middle troposphere appeared on that day over north Pakistan. The trough moved away northeastwards. The STR at 500 hPa level gradually shifted northwards and ran from north Pakistan to southeast-

ern part of the Plateau [Fig.1(d)] on 26 June. The STR at 200 hPa also shifted northwards and ran on that day roughly along Lat. 30°N. The ET in the lower troposphere developed to the south of the mid-tropospheric STR and ran from north Konkan to Gangetic West Bengal on 26 June. The ET broke the spell of stagnation and further advanced monsoon over Orissa, Bihar and east Madhya Pradesh on 28 June [Fig.1(a)].

Averaged contour heights and temperature anomalies at 500 hPa level are shown in Figs.1 (e & f) and that of contour heights and wind speed at 200 hPa level in Figs.1(g & h) for the period 10-22 June and 24-30 June, respectively. The periods correspond to hiatus period and subsequent advance of the monsoon. Hiatus period charts showed the following features :

(a) At 500 hPa a deep trough lay over India along Long. 77°E. Air temperatures over NW India and neighbourhood, and over Tibetan Plateau were 2° to 3°C below normal being greater than 4°C over western parts of the Plateau.

(b) The sub-tropical westerly jet stream core at 200 hPa level ran roughly along Lat. 37°N across Jammu & Kashmir and Tibetan Plateau.

At the time of further advance of the monsoon the charts showed the following features:

(c) STR at 500 hPa level ran roughly along Lat. 26°N across India. Air temperatures in the latitudinal belt of 25°N - 35°N over India excluding western Himalayas and adjoining Tibetan plateau became warmer by about °C, central parts of Tibetan plateau and adjoining India region being warmer by 2° to 3°C.

(d) At 200 hPa level the sub-tropical westerly jet core shifted to the north of Lat. 40°N.

3.1.2. *Stagnation of monsoon (18 June - 11 July, i.e., 24 days) during 1982*

In 1982 SW monsoon stagnated for 24 days south of Lat. 21°N and to the east of Long. 84°E shortening the total period of monsoon over NW India and west M.P. The stagnation caused delay of advance of monsoon by 25 to 30 days over west Madhya Pradesh and Gujarat states and by 15 - 20 days over Uttar Pradesh, Haryana, Punjab, Himachal Pradesh and east Rajasthan. The advance of the monsoon from 12 July is shown in Fig.2(a).

The locations of the troughs and ridges at 850, 700, 500, 300 and 200 hPa levels on 17 and 18 June as well as 9, 12, and 16 July, 1982 have been shown in Figs.2(b-f). It was observed that the STR in the upper troposphere lay between Lats. 20° N and 25°N across the country during the stagnation period. However, the middle tropospheric (500 hPa) ridge across India was absent up to 8 July.

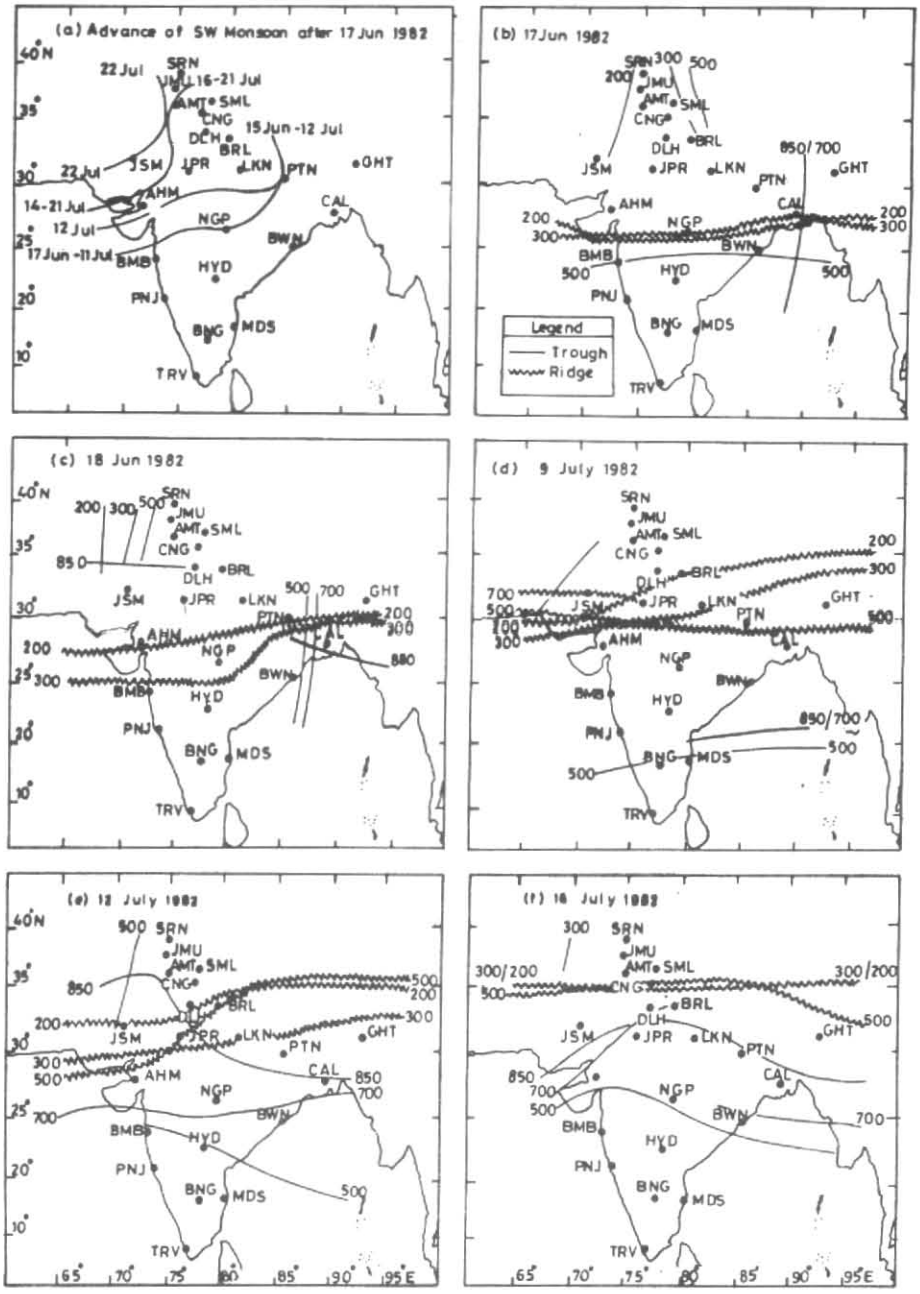
The dominant synoptic features during the stagnation period of 1982 were also due to the advent of mid-tropospheric westerly troughs in the Indian latitudes and their amplification to the south of the Tibetan plateau. The first trough appeared over Jammu & Kashmir and neighbourhood on 17 June. The northern part of the trough moved away around the northern periphery of the plateau. The southern part of the trough apparently took a southeasterly course around the southern periphery of the plateau, got amplified over the Indian sub-continent extending equatorwards to south of Lat. 15°N and moved away eastwards by 21 June. The zonal current at 500 hPa to the western side of the plateau appeared to have bifurcated into two branches- the northern branch took a northeasterly course, while the southern branch apparently took a southerly course around the barrier. Similar effect of the barrier was observed with the second (20 - 23 June) and the third (24 - 28 June) troughs. The fourth (4 - 7 July) and the fifth (12 - 14 July) troughs which existed to the north of lat. 25°N, were of quasi-stationary nature for a couple of days over NW India and then moved NE-wards across the Tibetan plateau.

The STR at 500 hPa level developed around Lat. 24°N across the country on 7 July. It gradually shifted over Tibetan plateau and neighbourhood and ran roughly along Lat. 30°N on 15 July. The upper tropospheric STR also gradually shifted northwards to Lat. 30°N around 16 July.

Consequent to the passage of the mid-latitude westerly troughs in the middle tropospheric levels across the country in succession, the ET in the lower troposphere was disorganised. In its place north-south oriented trough in the lower tropospheric equatorial westerlies developed over NE India and adjoining Bay of Bengal on 17 June and persisted there upto 7 July. The ET in the lower and middle tropospheric levels across the Indian region developed around Lat. 15° N on 9 July. It gradually moved northwards over north India and broke the spell of the stagnation of the monsoon.

During the period of stagnation and thereafter the following characteristic anomalous features in the wind field were observed:

(*i*) Till the end of June, lower and middle tropospheric westerly winds were stronger by 10-15 kt than its normal strength over India. The upper tropospheric easterlies were weaker than the normal strength.



Figs.2(a-f). (a) Advance of SW Monsoon during 1982, after 17 June and (b-f) Location of troughs and ridges at different levels (hPa) as marked on the lines (17, 18 June and 9, 12 & 16 July 1982)

(*ii*) During the first week of July, the equatorial westerlies in the lower troposphere became weaker than normal to the south of Lat. 22°N. In the upper troposphere stronger (10-15 kt) than normal easterly winds appeared in the latitudinal belt of 13° - 15°N.

(*iii*) During the second week of July, the easterly winds to the north of the ET upto mid-tropospheric levels became stronger by 5-10 kt than the normal. Stronger than normal westerly winds (5- 10 kt) appeared around lat. 10°N in the lower troposphere. The upper tropospheric belt of easterlies were 10-15 kt stronger than normal strength and extended up to lat. 20°N.

(*iv*) In the third week of July, the strong lower tropospheric westerly belt shifted northwards to Lat.

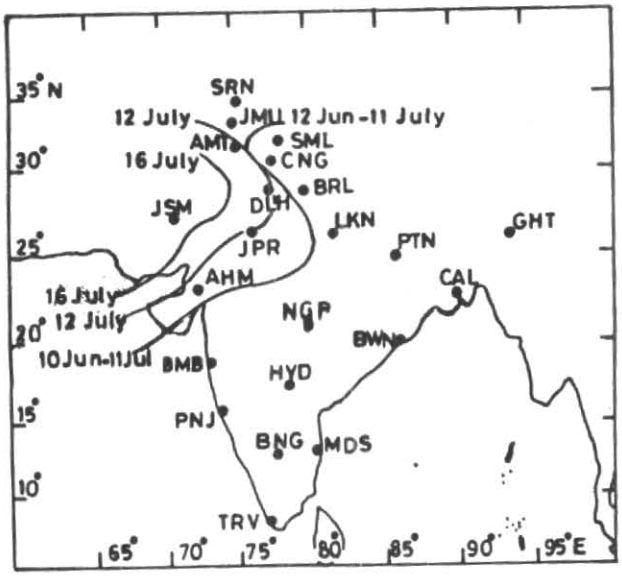


Fig.3. Advance of SW monsoon, 1991 after 12 July

15°N to 18°N. The easterlies in the upper troposphere continued to be stronger than normal to the south of lat. 15°N.

(*v*) The upper tropospheric westerlies to the north of the ridge appeared to be stronger by 10-15 kt than normal throughtout the period.

A low pressure area developed over NW and adjoining westcentral Bay on 8 July. It moved westwards across the country to Rajasthan breaking the spell of stagnation of monsoon. During the hiatus period, no tropical system developed over the Indian seas or the land areas.

3.1.3. *Stagnation of monsoon (13 June -10 July, i.e., 28 days) during 1991*

In 1991, advance of the monsoon stagnated for 28 days to the south of the northern limit of the monsoon (NLM) passing through Veraval-Ahmedabad-Ujjain-Khajuraho-Bareilly-Dehradun and Dalhousie. The stagnation shortened the period of monsoon over NW India and north Gujarat and caused deficiency in seasonal rainfall by 22 to 44 percent over Haryana, Rajasthan, Saurashtra and Kutch. The advance of monsoon after the stagnation period has been shown in Fig.3 and the ridge and trough positions on 10, 12 and 14 June and 10 & 12 July, 1991 are shown in Figs.4 (a-e). Averaged contour heights, winds and temperature anomaly charts of 500 and 200 hPa levels for the period 13-29 June and 10-20 July 1991 are shown in Figs. 4(f-i).

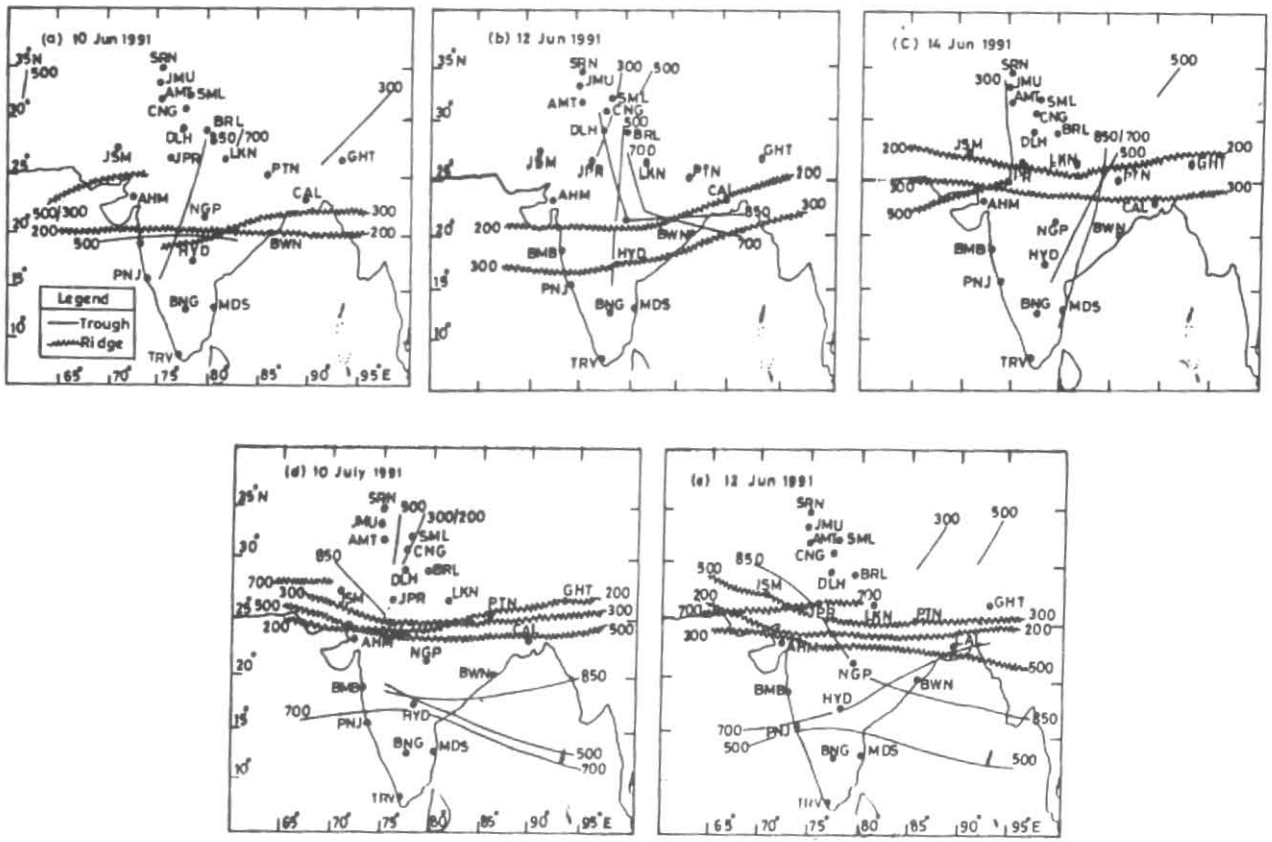
A monsoon onset vortex developed over southwest Bay, which moved over central Madhya Pradesh and weakened there. It advanced both the branches of monsoon over the country. The upper tropospheric STR ran roughly along Lat. 21°N across the country at the end of this advancing phase. During the second fortnight of June, the upper tropospheric STR was located between Lats. 25°N and 30°N to the east of Long. 80°E and between Lats. 22°N and 28°N to its west. The STR became more or less east-west oriented during the first fortnight of July and shifted to the north of Lat. 30°N on 15 July, *i.e.*, a few degrees north of the normal position.

At 500 hPa level the STR was mostly absent across India upto 7 July except to the west of Long. 75°E, where a weak STR prevailed between Lats. 25°N and 30°N from 27 June onwards.

The passage of three mid-tropospheric westerly troughs (11-20 June, 19-22 June, 1-14 July) across the Indian subcontinent and neighbourhood and their amplification to the south of the Tibetan plateau disorganised the ET. In its place north-south oriented trough in the monsoon westerlies developed over NE India. It prevailed upto 7 July. The equatorial westerly winds became stronger by 5-10 kt than the normal over the country by 14 June, which weakened to below normal strength in the latitudinal belt of 13° N to 20°N by the end of June, followed by a stronger (5-10 kt) than normal in the latitudinal belt to south of 13°N. Thus a cyclonic shear zone built up in the above latitudinal belt (13-20°N). The ET in the lower troposphere developed around Lat. 18°N on 8 July over Bay and adjoining Orissa in association with the formation of a cyclonic circulation over northwest and adjoining west-central Bay. The easterly winds to the north of the ET became stronger by 5-15 kt than the normal strength within a couple of days. The stronger (5-10 kt) westerly belt to the south of the ET extended upto Lat. 15°N in the lower troposphere.

The equatorial trough extended over NW India on 12 July, when the cyclonic circulation moved over NW Madhya Pradesh, thus breaking the spell of stagnation. During the period, easterly winds to the north of the ET became 15-20 kt more than the normal strength at 700 hPa and 10-15 kt at 850 and 500 hPa levels. Thereafter, a low pressure area formed over northwest Bay on 14 July which moved over south Rajasthan and neighbourhood on 19 July advancing the monsoon over the entire country. During the stagnation period cyclonic circulation (*i*) between 20-22 June and (*ii*) between 24- 27 June developed over the Bay of Bengal but they weakened *in situ*.

Averaged contour heights (gpm) and temperatures (°C) anomaly at 500 hPa level are shown in Figs.4 (f & g) and that of contour heights and wind speed at 200 hPa level in Figs.4(h & i) for the periods 13-29 June and 10-20 July respectively. The periods correspond to height of the hiatus



Figs.4(a-e). Troughs and ridges at different levels (hPa) as marked on the lines (10, 12, 14 June and 10, 12 July, 1991)

and the subsequent advance of the monsoon. During the hiatus period (13-29 June) the following features were observed:

(a) 500 hPa period - averaged chart showed a deep trough over India. Air temperatures over NW India and neighbourhood and over Tibetan plateau to the west of Long. 83°E were 1° C to 2°C below normal and over north Pakistan and over adjoining Afghanistan they were 3° C to 4°C below normal. They were about 2°C above normal in the latitudinal belt of 25°-30°N to the east of Long. 85°E.

(b) The sub-tropical westerly jet stream core at 200 hPa level ran along Lat. 35°N to the west of Long. 70°E and to its east between Lats. 35°N and 40°N. The westerly winds to the north of Lat. 25°N were 10-20 kt stronger than the normal.

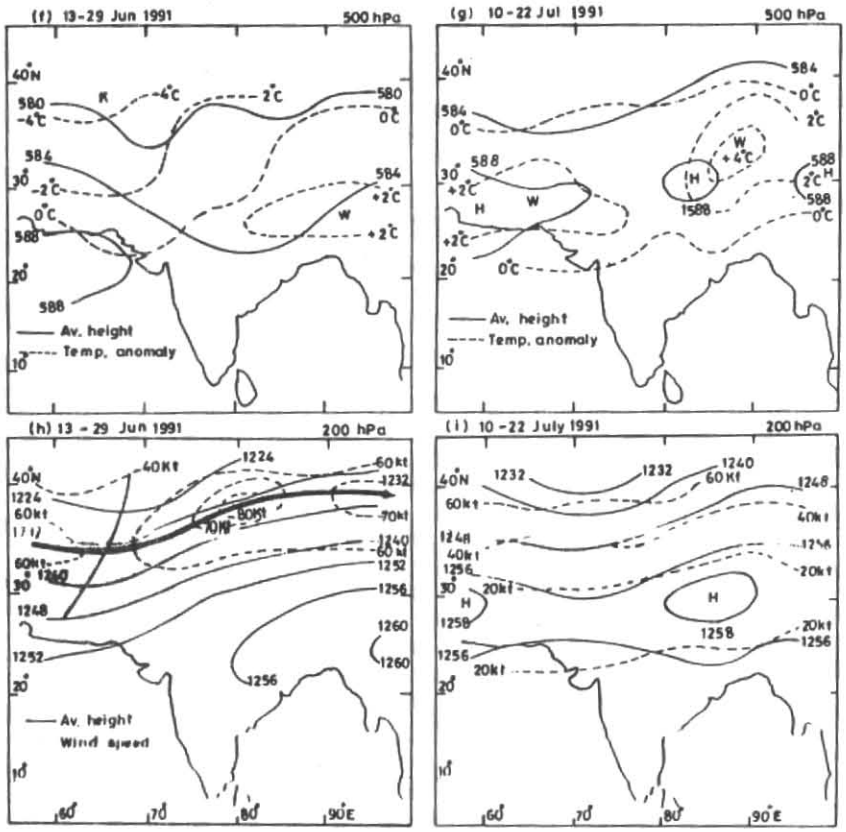
During the post hiatus period (10-20 July) the features showed the following characteristics:

(*i*) At 500 hPa level the STR ran roughly along Lat 30°N over India. Air temperatures between lats. 25°N and 35°N were 2°C above normal, being as much as 4°C above normal over eastern parts of the Tibetan plateau and neighbourhood.

(*ii*) At 200 hPa level the sub-tropical westerly jet core shifted to the north of Lat. 40°N. The easterly winds to the south of Lat. 22°N became stronger by 10-15 kt at the time of revival of the advance of monsoon.

3.2. *Study of the stagnation of monsoon during 1985*

The advance of SW monsoon during 1985 is shown in Fig.5. During the year 1985 though there was no prolonged stagnation (>15 days) of the advance of the SW monsoon as a whole, yet the Arabian Sea branch of the monsoon stagnated from 9 June to 13 July (35 days). There was a short lull in the advance of the Bay of Bengal branch of the monsoon over NE India between 16 and 24 June (9 days). The 500 hPa ridge was established along Lat. 26° N by 24 June. The equatorial trough became, prominent over the Bay



Figs.4(f-i). (f&g) 500 hPa averaged height (gpm)X10 and temperature anomaly (°C) and (h&i) 200 hPa averaged height (gpm)X10 and wind speed (kt)

of Bengal on 24 June, when a low pressure area developed over northwest & adjoining westcentral Bay. The low pressure area travelled over NE Madhya Pradesh and neighbourhood on 26 June and became unimportant there by 29 June. The system advanced the monsoon over Bihar, east UP, most parts of MP and Vidarbha upto 28 June.

A trough in mid-tropospheric westerlies between 27 June - 1 July and its amplification over north India, south of Tibetan plateau, arrested further advance of the monsoon till 7 July. During the first week of July two more troughs in the middle tropospheric levels moved across NW India and Tibetan plateau inhibiting the establishment of ET to the west of Long. 85°E. The ET became prominent on 11 July, when a cyclonic circulation in the lower and middle tropospheric levels developed over NW Madhya Pradesh and neighbourhood. It travelled westwards and became less marked over Pakistan by 15 July. This system further advanced the monsoon over Gujarat and NW India.

Averaged grid points contour heights and temperature at 500 hPa level and contour heights and wind speeds at 200 hPa levels for 13-18 June, 27-30 June and 8-15 July are shown in Figs.6 (a-c) and Figs.7 (a-c) respectively. Figs.6 (a & b) show westerly trough over India and below normal temperature over NW India and neighbourhood, while Fig.6(c) indicates the equatorial trough and no westerly trough in the Indian area, with warmer air in the latitudinal belt of 25°N to 30°N across the country.

Figs.7 (a &b) show that jet speed winds at 200 hPa lay over extreme north India and Tibetan plateau with its core approximately between Lats. 38°N and 40°N. Fig. 7(c) shows that the sub - tropical westerly jet stream moved north of the Lat. 40°N in the Indian longitudes. Thus the major stagnation of the Arabian Sea branch was accompanied by passage of 3 mid-latitude troughs over NW India between 12-15 June, 16-20 June and 27 June to 1 July.

3.3. *Advance of SW monsoon without prolonged stagnation- a case study of the advance during 1990*

During the year 1990 there was no prolonged stagnation in the advance of SW monsoon over the country. It set in over Kerala as early as May 19. There was short stagnation of the advance of the monsoon over peninsular India from 22 to 30 May (9 days). Thereafter, it gradually advanced

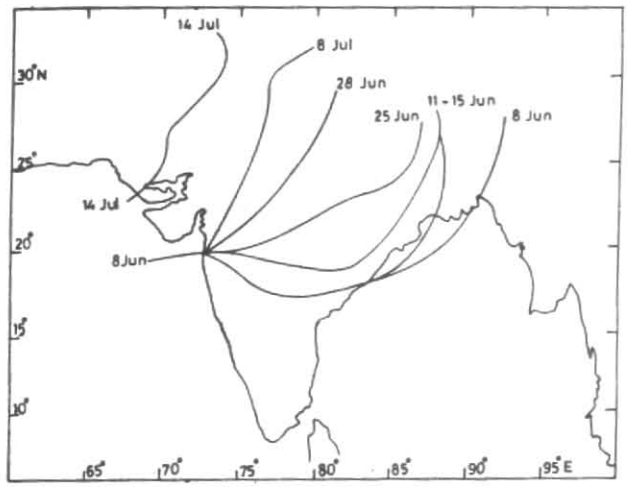


Fig.5. Advance of SW monsoon during 1985

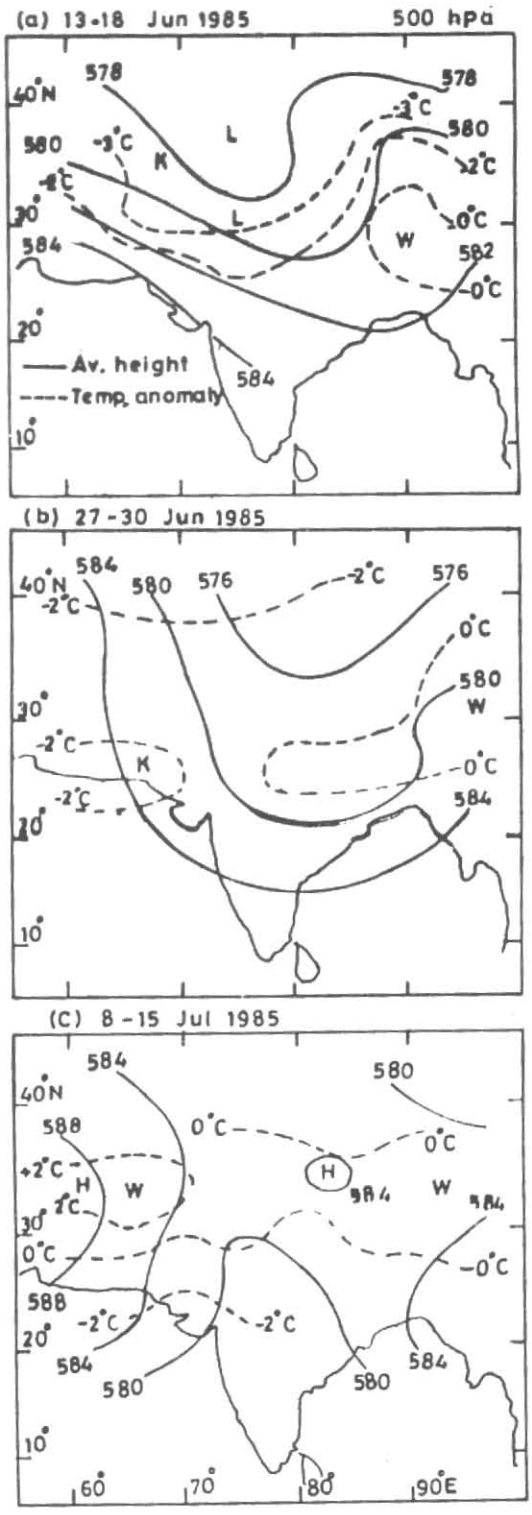
over the country by July 1. During the phase of advance it also stalled for 8 days from 7 to 14 June to the south of Lat. 20°N and to the east of Long. 89°E and for 7 days from 21 to 27 June, to the south of Lat. 22°N and east of long. 78°E Fig.8 shows the advance of the SW monsoon during 1990 and Figs.9 (a-e) show the position of troughs and ridges at 850, 700, 500, 300 and 200 hPa levels on 11, 15, 20, 26 and 30 June respectively.

The STR across the country in the upper tropospheric levels fluctuated between Lats. 20°N and 25°N during the first fortnight of June. During the period westerly winds to the north of the ridge were 10-30 kt stronger than normal, whereas the easterlies were weaker by 5-15 kt to the south of Lat. 20°N. During the second fortnight the STR shifted further northwards and lay around Lat. 30°N by the end of June. The easterly winds over India gradually strengthened to 10-20 kt above normal speed during the period.

In the early phase of advance (1-7 June) a quasi-stationary westerly trough in the middle and upper tropospheric levels prevailed to the north of Lat. 25°N between Long. 65° E and 75°E.

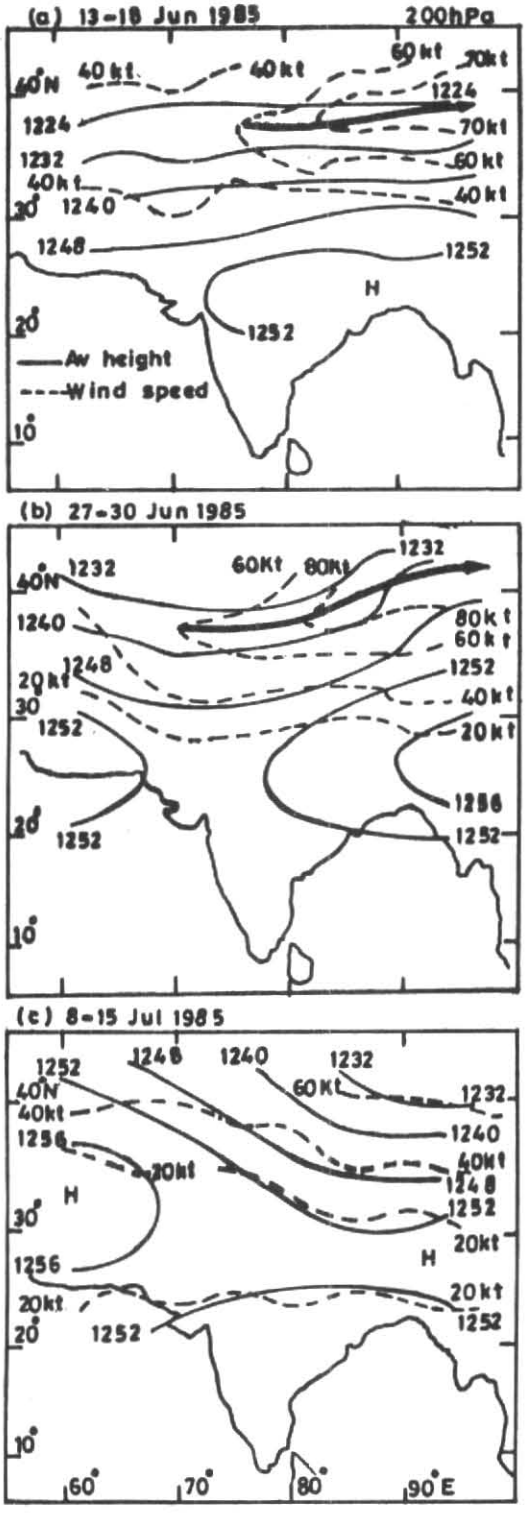
The amplification of the middle tropospheric trough (9-13 June) to the south of Tibetan plateau in the absence of the STR disorganised the equatorial trough in the lower tropospheric levels [Fig.9(a)] and arrested the further advance of the monsoon temporarily.

Figs. 9(b-e) show the gradual northward shifting of the middle and upper tropospheric ridges and lower tropospheric troughs from June 15 onwards. From the figures it became apparent that a well marked STR was established in the middle tropospheric level roughly along Lat. 26°N on 15 June. The STR at this level lay roughly along Lat. 27°N on 20 June. Two troughs in the mid tropospheric level, one between 18-24 June and the other between 26-30 June,



Figs.6(a-c). 500 hPa averaged height (gpm)X10 and temperature anomaly (°C)

moved over north India-Tibetan plateau. Their passages, though, displaced the STR temporarily to somewhat south-



Figs.7(a-c). 200 hPa averaged height (gpm)X10 and wind speed (kt)

ern latitudes, but could not destroy it. The westerly troughs did not penetrate south of 30°N after 22 June.

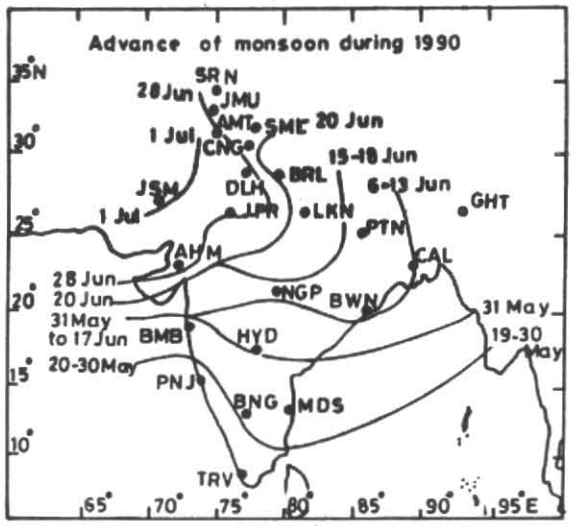
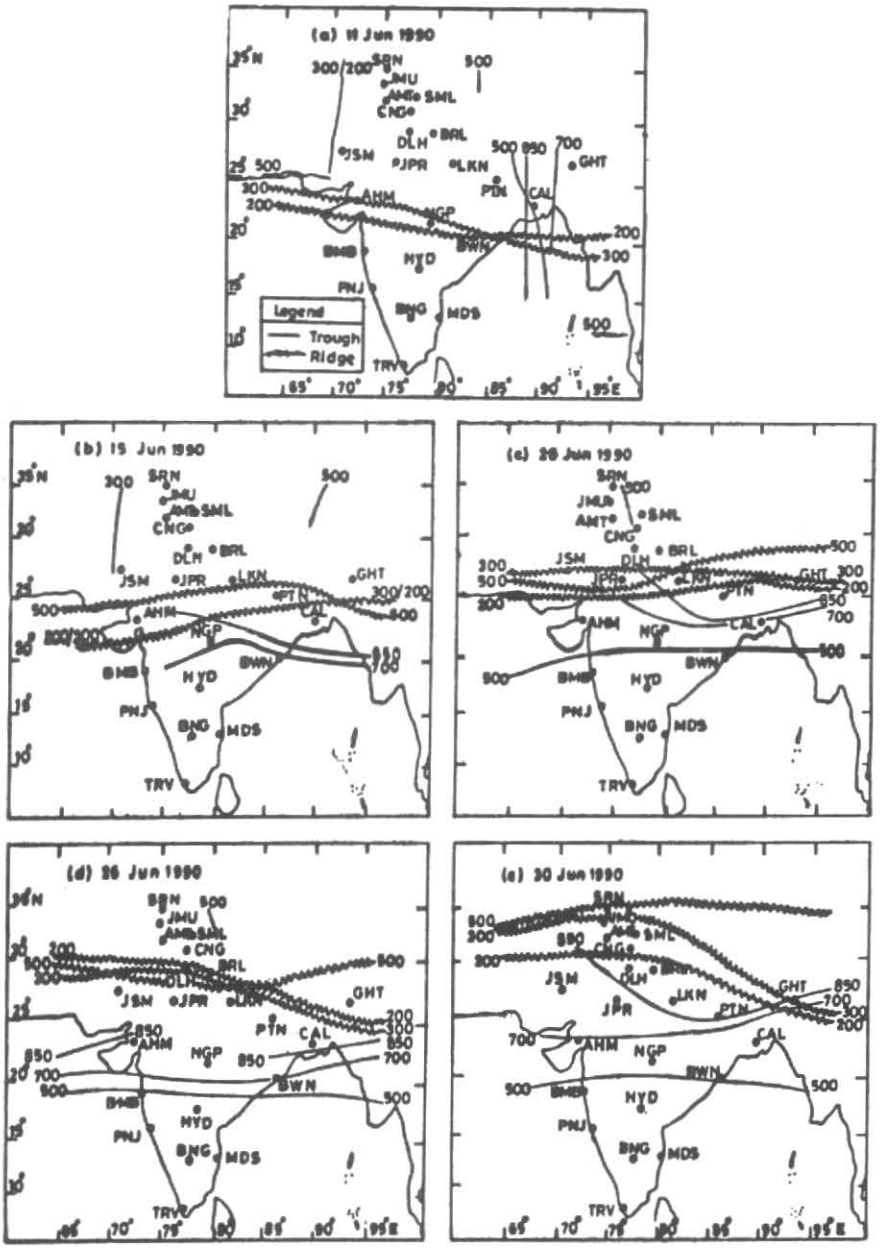


Fig.8. Advance of SW monsoon during 1990

The equatorial trough in the lower tropospheric levels, which was seen on 15 June, weakened by 17 June. The trough was well marked due to a deep depression (13-15 June) over north-west Bay and its subsequent westwards movement. It weakened over Bihar plateau on June 15. The equatorial trough again became well organised to the east of Long. 80°E on 20 June. It became well marked due to the formation of a well marked low pressure area on June 21 over Bihar plateau and neighbourhood. It initially moved eastwards under the influence of the westerly trough to north Bay and neighbourhood. After the trough moved away on 24 June, it started moving westwards and lay over south Uttar Pradesh and adjacent north Madhya Pradesh, where it weakened to June 30. On June 26, a cyclonic circulation in the lower and middle tropospheric levels developed over Gujarat and neighbourhood, which persisted there till June 30. These two systems intensified the equatorial trough on 28 June in the lower troposphere which advanced the monsoon over the entire country. The easterly winds in the lower troposphere were stronger by 10-15 kt over north peninsula and on plains of north India during the period 13-19 June and by 5-10 kt from 27 June to 3 July. In between the easterlies to the north of the trough weakened somewhat and were stronger by about 5 kt over plains of north India. However all the time westerlies in the lower troposphere south of 15°N were 5-10 kt stronger than normal strength.

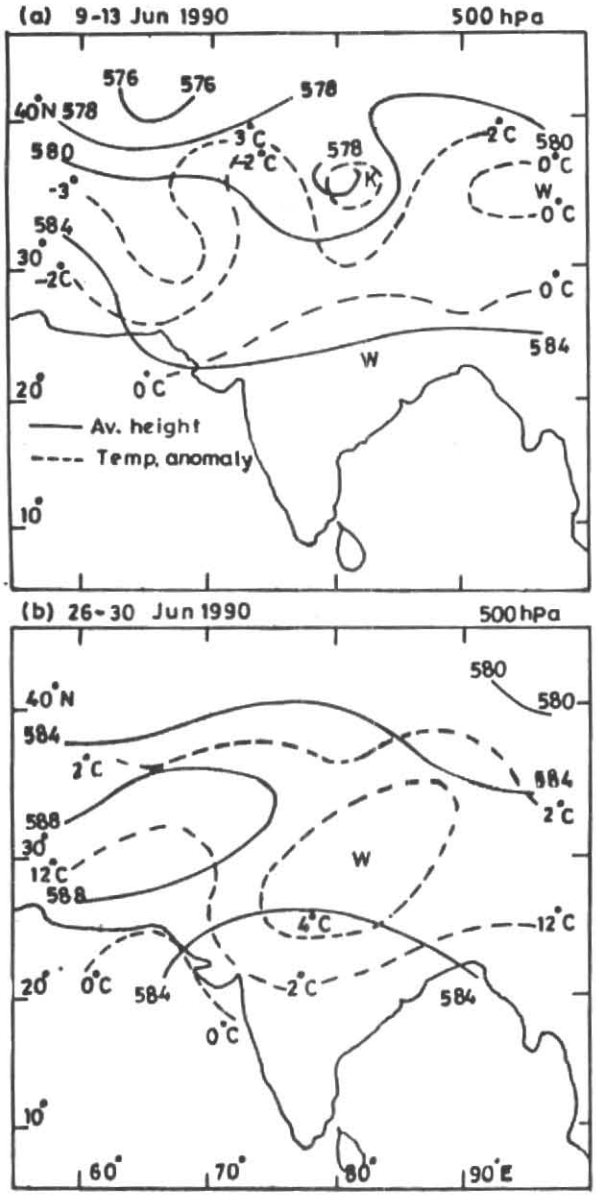
Figs. 10(a & b) show the average contour heights and temperatures from 9-13 June and 26-30 June respectively at 500 hPa level. Figs. 11(a & b) show the contour heights and wind speed at 200 hPa for the corresponding period. From these figures it could be observed that during the trough activity the air temperatures at 500 hPa level were 2° to 3°C



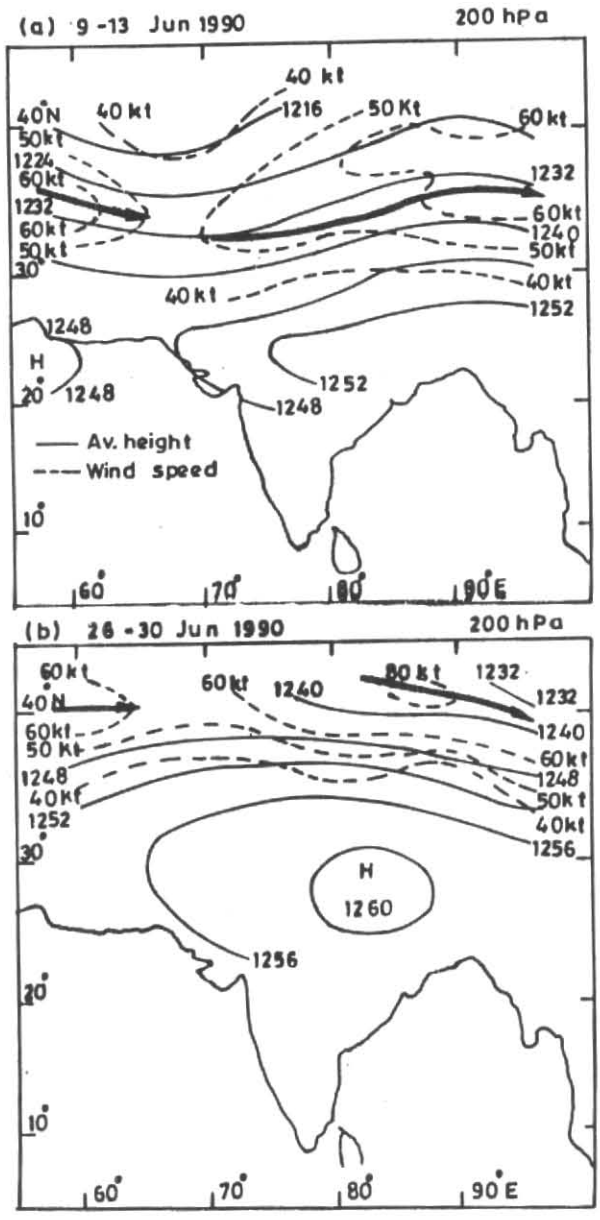
Figs.9(a-e). Troughs and ridges at different levels (hPa) as marked on the lines

below normal over Tibetan plateau. The averaged charts for the period 26-30 June showed that the air temperature between Lats. 25°N and 35°N became 2° to 4°C above normal at 500 hPa level and a ridge was well established at 200 hPa, the sub- tropical westerly jet core shifted to Lat. 40°N during the same period.

Thus, a remarkable feature of the early summer season in 1990 over the Indian region was the fact that the Tibetan plateau was warmer than normal after mid-June and was not much influenced by the activity of the sub-tropical westerly troughs in the middle and upper troposphere. This was indeed responsible for the gradual advance of the monsoon and the absence of a prolonged stagnation in the advance of the monsoon across the country. Thus the warming of the middle troposphere over the Tibetan plateau and establishment of middle tropospheric STR across north India could be important factors for the smooth advancement of the monsoon across India in the regular formation and



Figs.10(a&b). 500 hPa averaged height (gpm)X10 and temperature anomaly (°C)

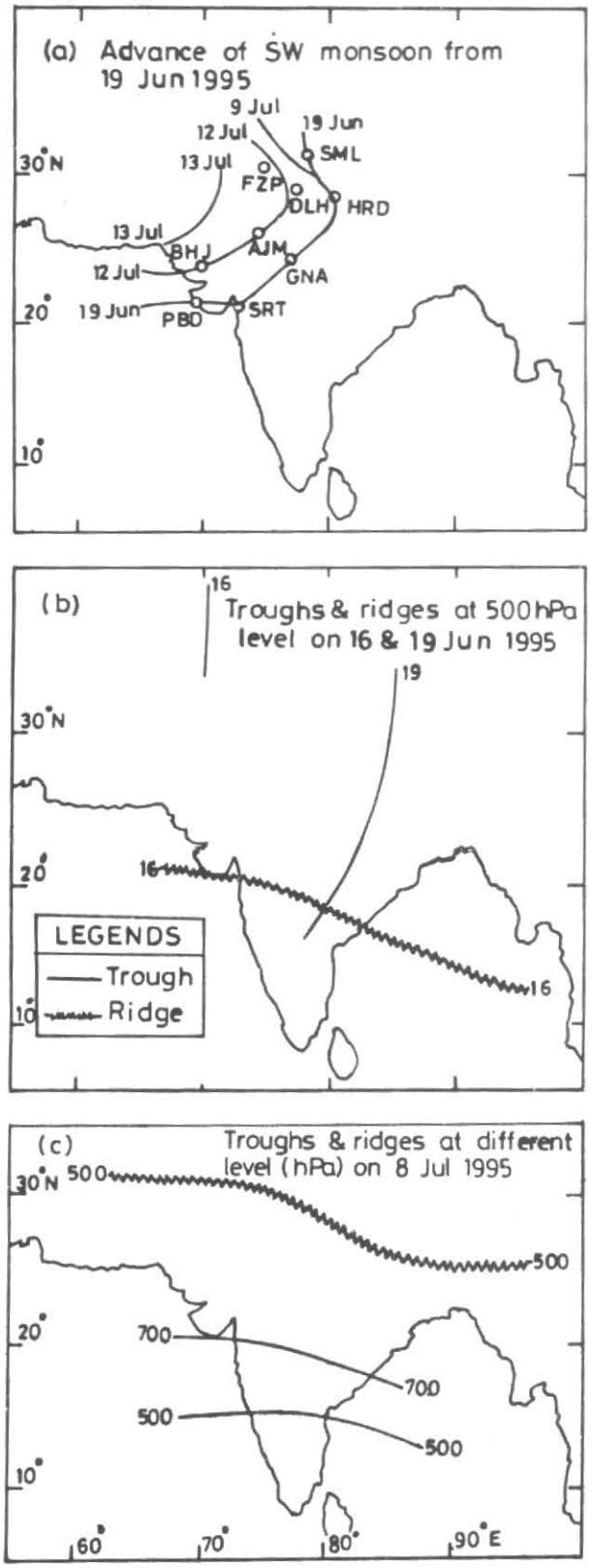


Figs.11(a&b). 200 hPa averaged height (gpm)X10 and wind speed (kt)

movement of synoptic scale disturbances within the equatorial trough during June- particularly after mid-June.

3.4. *Stagnation of monsoon during 1995 (20 June - 8 July)- a test case study*

The stagnation of SW monsoon outside NW India and adjoining west Uttar Pradesh, west Madhya Pradesh and north Gujarat during 1995 was examined as a test case. Advance of monsoon from 19 June 1995 onwards has been shown in Fig.12 (a). Troughs and ridges at 500 hPa level for 16 and 19 June 1995 have been shown in Fig.12(b). On 16 June, a trough in mid tropospheric westerlies appeared over north Pakistan when the STR lay to the south of Lat. 20°N across the country. The westerly trough, subsequently, amplified to the south of the Tibetan plateau and extended from Bihar plains to Rayalaseema across east Madhya Pradesh on 19 June. Two more mid tropospheric westerly troughs (20-25 June, 30 June-2 July), while moving across the Indian latitudes, amplified to the south of the Tibetan plateau. Passage of those troughs disorganised the ET and inhibited its formation over north India to the west of Long. 80°E, arresting the advance of monsoon over NW India and neighbourhood.



Figs.12(a-c). (a) Advance of SW monsoon from 19 June 1995 and troughs and ridges at (b) 500 hPa level on 16 & 19 June 1995 and (c) at different levels on 8 July 1995

The mid-tropospheric STR established over NW India to the north of Lat. 25°N on 6 July. The ET at 700 hPa established along Lat. 19°N on that day. On 8 July the mid-tropospheric STR shifted to the north of Lat. 30°N over NW India and neighbourhood and the ET at 700 hPa slightly to the north of Lat. 20°N [(Fig.12 (c)]. Thus the spell of stagnation broke and the monsoon gradually advanced over NW India and neighbourhood from 9 July onwards.

These sequences confirm the conclusions drawn earlier that the prolonged stagnation of the monsoon is due to the passage of mid tropospheric westerly troughs in succession, their amplification to the south of Tibetan Plateau and the absence of STR over north India. These features together result in disorganisation of the ET and cause hiatus in advance of monsoon.

4. Discussion

The present case studies revealed that the advance of the summer monsoon over the Gangetic valley and NW India is associated with the establishment of an active ET across India and building up of a strong STR to the north of Lat. 25°N in the middle troposphere. It is believed that the warming up of the Tibetan plateau is one of the reasons for the establishment of the STR throughout the middle and upper troposphere. The location of the mid-tropospheric STR during the onset and advance phases of the monsoon appears to be very crucial during the advance phase of the monsoon. In particular, location of STR over north India or the absence of the same plays a pivotal part on the advancing monsoon regime. Similarly mid-tropospheric activities, in particular, the mid-latitude westerlies troughs and the mid-tropospheric STR, are significant synoptic forcings along with the mechanical forcing of the Himalayan massif and the elevated Tibetan plateau, which determine the monsoon advance in the Indian subcontinent. In such synoptic situations, the effect of the mechanical barrier of the Himalayan massif and the elevated Tibetan plateau on the mid-tropospheric westerly troughs are also important in adversely affecting the advance of monsoon.

The mid-tropospheric westerly trough, on reaching over Jammu & Kashmir and neighbourhood, is bifurcated over there due to the barrier effect of the massif - the northern part continues to move along the northern periphery of the plateau while the southern part is forced to move around its southern periphery. In the course, the southern part is amplified over the Indian sub-continent around Long. 80°E or to its east extending equatorwards as far as up to Lat. 15°N. This amplified westerly trough inhibits the northward migration of the ET as the thermal structure, associated with the STR, for the advance of the monsoon is temporarily

annihilated over the sub - continent and the Tibetan plateau. Further, in such a situation the sub-tropical westerly jet core at 200 hPa appears between Lats. 35°N and 40°N running from Jammu & Kashmir to NW China across Tibetan plateau and the easterlies in the upper troposphere over the Indian Peninsula become weaker than the normal. Also, the trough activities lower the 500 hPa air temperature by 2° to 4°C from normal over India and neighbourhood (to the north of Lat. 25°N and east of Long. 85°E).

Prior to the commencement of the next phase of advance of monsoon, the STR in the middle and upper troposphere becomes well marked over north India and adjoining Tibetan region. When the mid-tropospheric trough activity in the region ceases or the troughs move across further northern latitudes (north of Lat. 35°N), the air temperatures at 500 hPa level become warmer to the north of Lat. 25°N particularly over Tibetan plateau and neighbourhood. At that time, in the lower tropospheric monsoon current, a cyclonic shear zone appears between Lat. 10°N to 20°N, a couple of days earlier to the restoration of the ET. After the formation of well organised ET a synoptic system develops which moves westwards and breaks the spell of stagnation.

5. Conclusions

(*i*) Establishment of a strong mid-tropospheric STR over north India and adjoining Tibetan plateau after mid-June is a key factor in maintaining the ET or the monsoon trough over the country. This is conducive for the progressive advance of the monsoon over the country.

(*ii*) In the absence of a strong mid-tropospheric STR over north India, the mid-tropospheric westerly troughs propagate equatorward frequently across north India. This causes the advance of the monsoon to be slowed down or halted. This is in agreement with the findings of Krishnamurty and De (1993) regarding the erratic advance of the ISM.

(*iii*) The mechanical barrier of the Himalayan massif and the Tibetan plateau tend to bifurcate the westerly troughs and to amplify its southern part over Indian region around Long. 80°E and to its east. This phenomenon is favourable in halting the monsoon advance as the synoptic forcing in the form of a strong STR, required for the advance of monsoon, is absent.

(*iv*) The presence of sub-tropical westerly jet core between Lat. 35°N and 40°N at 200 hPa across NW India and Tibetan plateau and the weaker upper tropospheric easterlies over India are indications of weak monsoon activity over the region and the consequent stagnation in further advance of the monsoon.

(*v*) The warming up of the Tibetan plateau and its surroundings by the middle of June is conducive for the establishment of the Tibetan anticyclone and for the advance of the SW monsoon.

(*vi*) The monsoon activity and the advance of monsoon (after temporary stagnation), revives after the establishment of a well marked ET in the lower and middle troposphere.

(*vii*) The sub-tropical westerly jet core shifts north of Lat. 40°N during the revival phase of the monsoon advance.

(*viii*) The unusual stagnation of the Arabian Sea branch of the monsoon over north Konkan appears to be associated with the persistant activity of mid-latitude troughs in westerlies over Pakistan and adjoining NW India.

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