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The severe drought over Tamil Nadu during the retreating monsoon period of 1968 and its associations with anomalies in the upper level flow patterns over the northern hemisphere

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ABSTRACT. The mean contours and isotherms over the Indian sub-continent at the 850-mb and 300-mb levels and the moisture-content of the air over Tamil Nadu in November 1968 (a month of severe drought in that State) and in November 1966 (a month of fairly good retreating monsoon rainfall over the same area) have been discussed. The daily 700 and 500-mb charts for the Indian sub-continent, the 300 and 200-mb charts for Asia and Europe and the monthly mean 700-mb charts for the northern hemisphere during the same two months have also been studied. It has been shown that, during the drought month, the Subtropical Jet Stream System (STJS) was not only in unusually low latitudes over India but it was also markedly stronger than usual. This abnormality in the STJS was directly or indirectly associated with large-scale anomalies in the upper level flow patterns in the atmosphere over the middle and higher latitudes in the northern hemisphere. The genesis of these anomalies has been traced back step by step as far west as the United States of America.

The anomalous fluctuations of the STJS were indirectly responsible for the cyclonic storms in the Bay of Bengal being 'steered away' from Tamil Nadu and were thus also partly responsible for the drought conditions over Tamil Nadu.

The observed progressive trend of equatorward movement of the STJS along with the polar front jet and a deep cyclonic vortex in the subpolar latitudes in November 1968 has been discussed in relation to the progressive increase in the rainfall deficiency over Tamil Nadu during the same period. It has been suggested that the parameters utilised in the present study could be tried out in medium range forecasting of rainfall over Tamil Nadu during the retreating monsoon period.

1. Introduction

The State of Tamil Nadu in India covers an area of 129,900 sq. km and was till recently known by the name of 'Madras State'. Fig. 1 shows the area covered by this State.

Over most of India, the period, June to September, which is referred to in Indian meteorological literature as the southwest monsoon period is the principal rainy season. The principal rainy season over Tamil Nadu is, however, October to December. This period is referred to in scientific literature as the retreating monsoon period. The lay man however, often refer to the rainfall over Tamil Nadu during this period as the northeast monsoon rainfall. This is because, the retreating monsoon air circulates around the seasonal low over the south Bay of Bengal and consequently blows over and near Tamil Nadu from a northeasterly direction. The retreating monsoon rainfall over Tamil Nadu is very important from the point of view of agricultural production. It will, therefore, be a great step forward in forecasting, if the basic causes of deficient rainfall over Tamil Nadu during this important period can be unravelled.

During the retreating monsoon period of 1968, Tamil Nadu experienced severe large-scale drought*, the total rainfall during that period, being as much as 36 per cent in defect. In contrast to this, the retreating monsoon period of 1966 was characterised by abundant rainfall over the same area, the total rainfall during that period, being 27 per cent in excess. It was therefore considered worthwhile to examine whether the anomalies in the northern hemisphere flow patterns during November 1968 and 1966 could throw light on the very different rainfall regimes during these two retreating monsoon periods. As far as the writer is aware, this is the first** detailed synoptic study so far undertaken on the variability of rainfall during the retreating monsoon period in

*In this paper, the term 'drought' is used in the same sense as the term 'large deficiency in rainfall'. The former term has been preferred as it is shorter and therefore more convenient to use.

** Several of the results reported in this paper were presented by the author in May 1969 in a Symposium organised at New Delhi by the National Institute of Sciences, India (now known as the Indian National Science Academy) on 'Planning for Drought Areas".

Fig. 1. Tamil Nadu and neighbourhood

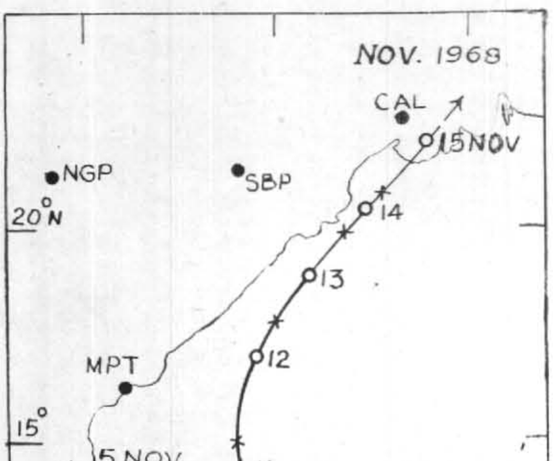

Fig. 2. Neither of the cyclonic storms shown in this diagram entered Tamil Nadu

relation to flow patterns over the northern hemisphere. It may be added that Rao (1963) had earlier studied the rainfall over Tamil Nadu in relation to hemispheric flow patterns by means of Hovmöller diagrams for the 500-mb level for the years 1946 and 1949. During those years, however, aerological reports from countries to the north of India were extremely scanty. The present study, on the other hand, is based on high level contour charts for 300 and 200-mb levels (besides those for the lower standard isobaric levels), utilising the far more abundant data which were available in 1966 and 1968 to the north of India after the WMO Northern Hemisphere Exchange System came into operation with New Delhi as one of the Exchange Centres.

2. Technique adopted for the study

An examination of the rainfall week by week during the retreating monsoon periods of 1966 and 1968 showed that the maximum contrast in the rainfall during these two periods, *taking one calendar month as a unit*, occurred in the month of November.

A comparative study was, therefore, made of the mean monthly flow-patterns over India and Pakistan in November 1966 and November 1968 at 850 and 300-mb levels which were readily available. The daily and the monthly mean tephigrams of Madras, for the above-mentioned two months, were also analysed. The mean 700-mb charts for the northern hemisphere, the daily 700 and 500-mb charts for the Indian sub-continent, the 300 and 200-mb charts for Asia and Europe for 00 and 12 GMT in November 1966 and 1968 (240 charts in all) were also studied with special reference to the Subtropical Jet Stream System (STJS), its anomalous fluctuations and the relationship between these fluctuations and the flow patterns over the rest of the northern hemisphere. The STJS may be defined for our purpose, as the westerly circulation affecting Indian latitudes in which the wind speed and lateral shear, at least in some segments, satisfy the WMO specifications for a jet stream (Reiter 1963).

3. Weather over Tamil Nadu associated with cyclonic storms

The cyclonic storms which developed in the Bay of Bengal and the Arabian Sea in November 1968 and November 1966 are shown in Figs. 2 and 3 respectively. In November 1968 — the drought year — two cyclonic storms developed in the Bay of Bengal. One of them moved northwestwards and crossed the coast much to the north of the city of Madras which lies in the extreme northeast corner of Tamil Nadu (*see* Fig. 1). The other cyclonic storm recurved to the northeast, far away in the sea-area itself and moved towards West Bengal and East Pakistan. In contrast to this, three out of the four cyclonic storms which developed in the Bay of Bengal in November 1966, moved west or westnorthwest. Two of them crossed the coast in Tamil Nadu itself and one very near the city of Madras. The cyclonic storm which developed in the first week of the month even dipped southwestwards after entering Tamil Nadu (*see* Fig. 3). It

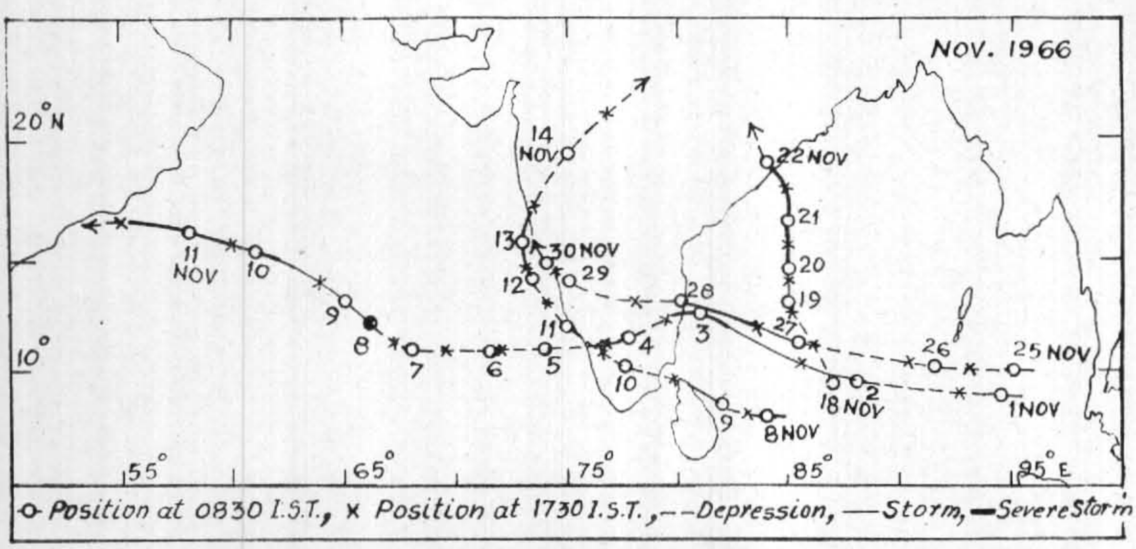

Fig. 3. The severe cyclonic storm of 1-11 November 1966 moved westsouthwestwards into Tamil Nadu after crossing the coast between Madras and Pondicherry (*See* Fig. 1)

is well-known that in cyclonic disturbances of the retreating monsoon period heavy rainfall occurs in the northern sector of the systems. It is therefore reasonable to infer that the different directions of movement of the cyclonic storms in November 1968 and November 1966 should, apart from other causes, have contributed to the contrasts in the rainfall during the above mentioned months — a conclusion supported by the earlier work of Rao (1953) and Rao and Jagannathan (1953).

4. Contours and isotherms over the Indian sub-continent

Fig. 4 shows, side by side, the mean 850-mb and 300-mb contours, contour anomalies and isotherms over India and Pakistan in November 1968 and November 1966. These are reproductions of charts published by the India Meteorological Department (1969 and 1967). The mean monthly patterns show the following —

850-mb level (*Figs. 4a and 4b*) — At this level, we may assume that easterlies represent moist air and westerlies, continental air in the retreating monsoon period over the Indian Peninsula. It is, therefore, reasonable to argue that the 1520 gpm line in Fig. 4 (a) roughly represents the mean boundary between continental air and moist air over the Peninsula in November 1968. Likewise, the 1500 gpm line in Fig. 4(b) roughly represents the mean boundary between moist air and continental air in November 1966. On this basis, it can be stated, that, in November 1968 — the month of severe drought in Tamil Nadu — continental air had, in the mean, invaded Peninsular India equatorward roughly upto Lat. 18°N while in November 1966— the month of fairly good rainfall — continental air had not pervaded equatorward beyond 25°N. These findings are consistent with those reported by Thiruvengadathan (1965) earlier.

300-mb level (*Figs. 4c and 4d*) — In November 1968, there was a closed high over southwest Bay of Bengal, the extreme south of the Peninsula and the adjoining parts of southeast Arabian Sea, *i.e.*, significantly to the *south of the normal position* of the subtropical ridge in November. Consistent with this, there was a 'solid' westerly flow to the north of the closed high and extending equatorward at least upto 18°N. The mean westerlies were 15-20 kt higher than normal in speed and the mean temperatures were 4° to 5° C below normal over the region of westerlies (India met. Dep. 1969).

In contrast to the above, there was no closed high in low latitudes at the 300-mb level in November 1966. The mean subtropical high lay as an extensive system with the ridge line to the *north of its normal position* (India met. Dep. 1967). The mean belt of westerlies was about 9 degrees to the north of its position in November 1968 (*see* the position of the 9640 gpm contour in the two diargrams).

5. Mean moisture content of the air over Tamil Nadu

Fig. 5 shows the mean dry bulb and dew point curves of Madras between the surface and 800-mb levels during (*i*) 1-15 November 1968 and 1966; (*ii*) 16-30 November 1968 and 1966 and (*iii*) 1-30 November 1968 and 1966.

Table 1 gives the *mean* mixing ratios over Madras at the standard isobaric levels during the above mentioned periods. The figures have been rounded off to the nearest gram per kilogram of

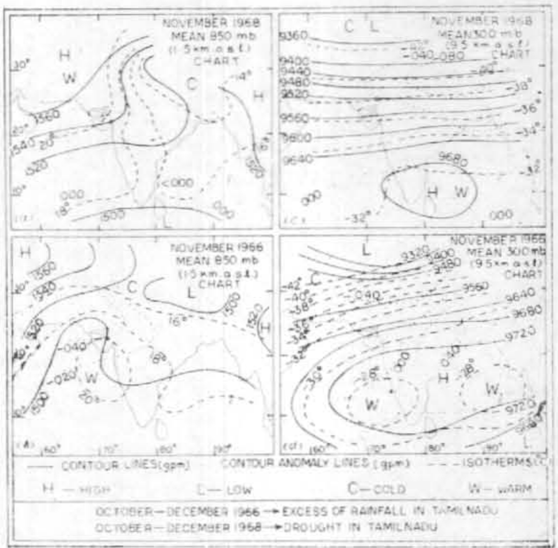

Fig. 4. The positions of the 1520 gpm contour in November 1968 (Fig. 4a) and 1500 gpm contour in November 1966 (Fig. 4b) at the 850-mb level. The 1520 gpm line may be taken to represent roughly the mean boundary between continental air and moist air over the Peninsula in November 1968. Likewise, the 1500 gpm line in November 1966 roughly represents the mean northern boundary between moist air and continental air in November 1966.

Note that the *minus* 32°C isotherm (and correpondingly also the isotherms of higher *negative* values) at the 300-mb level is in much more southerly positions in November 1968 (Fig. 4c) than in November 1966 (Fig. 4d).

dry air in accordance with the current practice in the India Meteorological Department. The mixing ratios have been read off from the tephigrams.

The mean moisture content of the air at any particular isobaric level is the same (within the limits of observational error) during November 1968 and 1966, except for the following minor differences —

(*a*) The moisture content in the first half of November 1966 is very slightly higher than in the second half of the same month. This may be due to the fact that the retreating monsoon was much more active in the first half than in the second half of that month.

(*b*) The moisture content is very slightly lower in November 1968 — the drought month — than in November 1966 — the month of farily good rainfall — at the 1000 and 850-mb levels. One should *prima facie* have expected this difference and in fact, much more, not only at these two levels but also at other levels. On the contrary, the values are the same at the 900 and 800-mb levels.

The important conclusion which we arrive at from this analysis is that the severe drought over Tamil Nadu was caused not by the deficiency of moisture as by the absence of suitable mechanisms to lift the available moisture to levels where they could condense to give rainfall. This aspect of the mechanism of monsoon rainfall had been emphasized earlier and also reemphasized recently (Ramaswamy 1958, 1969).

TABLE 1

Mixing ratios (gm/kg) of dry air

Isobaric levels (mb)	1-15 Nov 1968	1-15 Nov 1966	16-30 Nov 1968	16-30 Nov 1966	1-30 Nov 1968	1-30 Nov 1966
1000	16	18	16	17	16	17
900	12	13	12	11	12	12
850	11	11	10	10	10	11
800	8	9	9	8	9	9

6. Possible factors in the lower and middle troposphere which led to deficient rainfall in November 1968

Before discussing the drought situation with reference to the northern hemisphere jet stream systems, for the sake of completeness we shall make a general examination of the flow patterns in the lower and middle troposphere with a view to finding out, if possible, factors in these layers which might have contributed in the deficiency of rainfall in November 1968. We have already discussed the 850-mb level in an earlier section. We shall, now discuss the flow patterns at the 700 and 500-mb levels only.

Table 3 shows that the percentage deficency of rainfall in November 1968 was highest in the last

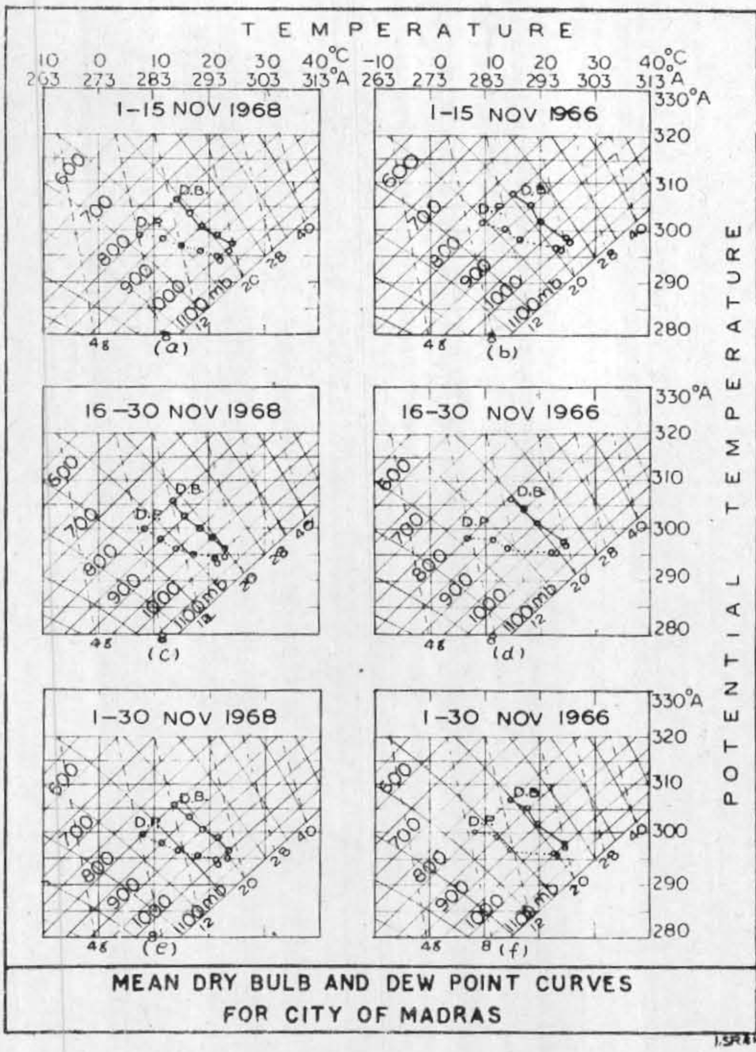

Fig. 5. The run of the dewpoint curves are not very different in the diagrams for November 1968 as well as 1966. For a comparison of mixing ratios, *see* Table in text.

ten days of the month (*viz.* 21-30 November). Let us summarise the observed synoptic features during this period.

700-mb level (21-30 November 1968) — This period was completely free from cyclonic storms in the Bay of Bengal. A few low pressure systems wuich moved from west to east, were feeble and affected only the extreme tip of the Peninsula. Hence there was no convergence in the windfield over Tamil Nadu except in the extreme south.

700-mb level (21-30 November 1966) — One severe cyclonic storm developed in the Bay of Bengal and struck Tamil Nadu (Fig. 3). The flow patterns over Tamil Nadu were continuously changing with the movement of the cyclonic storm. Marked convergence occurred in the windfield over Tamil Nadu on 27th and 28th in association with the cyclonic storm, causing heavy rainfall over Tamil Nadu.

500-mb level (21-30 November 1968) — The flow patterns resembled those of the 300-mb level (*vide* Fig. 4). Strong westerlies dominated the field north of 20°N over the Indian sub-continent and a closed high prevailed to the south of the westerlies. After the 23rd, a trough developed in the westerlies to the north of India with its axis between 70°E and 80°E and extended equatorward upto 18°N on 28th. It correspondingly shifted the high further equatorward. It was difficult to estimate even qualitatively , the extent of convergence or divergence in the field of the westerlies. A more detailed examination was necessary for this purpose but, as stated earlier, this was beyond the aim of the present paper and was therefore not attempted.

500-mb level (21-30 November 1966) — The cyclonic storm referred to earlier, extended from the surface upto 500-mb level. In the absence of cyclonic disturbances, the wind flow was NE/E

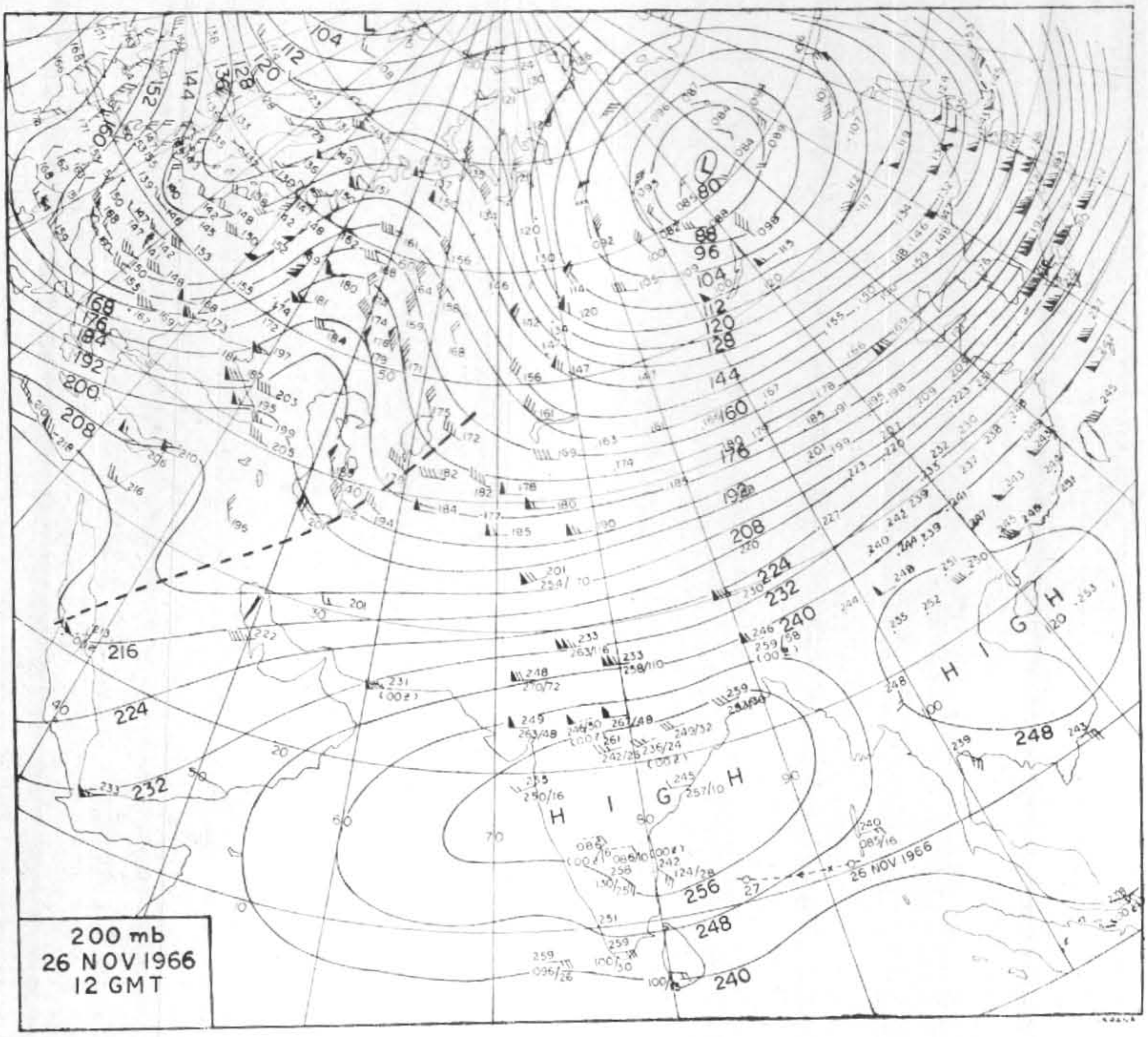

Fig. 6. The three figures near or above the station circle represent the contour heights in tens of gpm : 242 means 12420 gpm. The figures *below* the station-circle in the case of Indian stations represent the direction and speed of the wind at the 200-mb level. Almost all the data refer to 1200 GMT. The arrows with broken barbs represent 0000 GMT observations of the same day. The track of the depression between 26 and 27 November 1966 over the Bay of Bengal is shown by a broken line with an arrow indicating the direction of movement. The circle in the track represents the 0300 GMT position and the cross represents the 1200 GMT position of the depression at sea level.

Note that the Pamir trough has extended westwards to the Red Sea. The sub-tropical high is extensive and covers most of the Indian sub-continetnt, the Bay of Bengal and the Arabian Sea. Compare it with the relatively small high pressure cell over the Andaman Sea on the same date 26 November but in 1968, in Fig. 8.

over Tamil Nadu at the 500-mb level. The bulk of the rainfall was associated with the cyclonic storm which, as stated earlier, entered Tamil Nadu itself.

General (21-30 November 1968 and 1966) — The examination made above thus shows that non-occurrence of cyclonic storms resulted in absence of convergence in the lower troposphere and that this was an important factor in the lower troposphere in the development of the drought in November 1968. The variations in the moisture content of air in the two months November 1968 and 1966, did not account for the difference in the rainfall in these two months. At the 500-mb level the extension of the westerlies equatorward and the associated adjustments in the wind field, were possibly contributory factors in the development of the drought in November 1968.

7. Steering of the cyclonic storms in the Bay of Bengal

During most days in November 1968 and 1966, the 200-mb level lay *above* the layers which participated in the circulations associated with the cyclonic disturbances which developed and moved in the Bay of Bengal and the Arabian Sea. It was found — so far as this could be done with the data

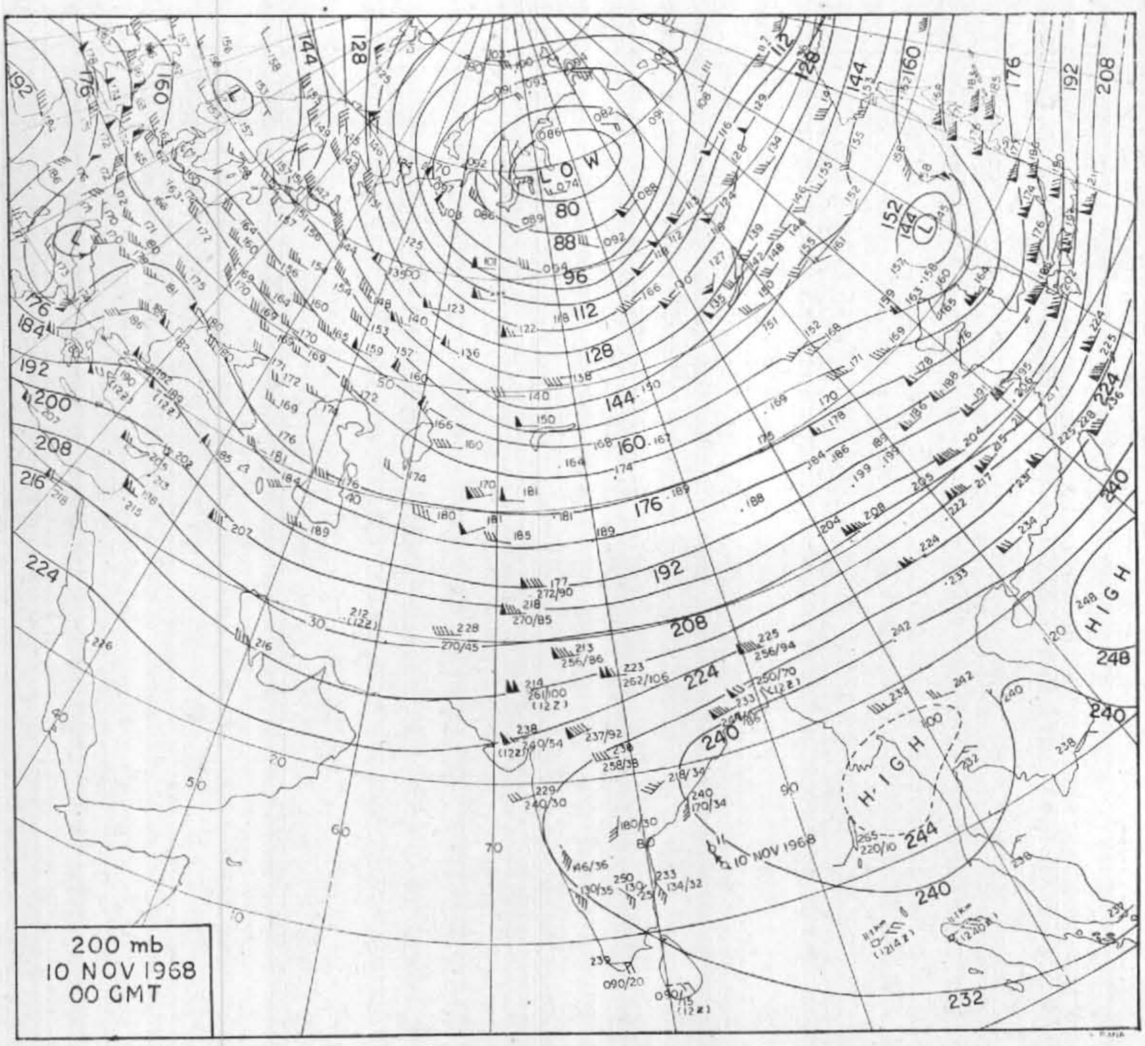

Fig. 7. Convention in plotting is the same as in Fig. 6. Almost all the data refer to 0000 GMT. The arrows with broken barbs represent 1200 GMT observations of the same day. The broken barbs against rectangles over and off North Sumatra are aircraft observations near about 200-mb level. The track of the severe cyclonic storm between 10 and 11 November 1968 over the Bay of Bengal at sea level is shown by a thick continuous line.

Note the abnormal position of the core of the subtropical high over the north Andaman Sea and lower Burma, the run of the contours over the Bay of Bengal and how they roughly indicate the direction of movement of the recurving cyclonic storm.

available*, — that the cyclonic storms and depressions in the Indian Seas in November 1966 and November 1968 were broadly "steered" by the subtropical anticyclonic system at the 200-mb level. When the cyclonic disturbance at sea level in south Bay was moving westnorthwest, the central region of the subtropical high at the 200-mb level lay further to the north and the flow patterns at the 200-mb level over the centre of the cyclonic disturbance at sea-level, "steered" the cyclonic system towards Tamil Nadu. On the other hand, when the cyclonic system was curving to the north or northeast, the position and configuration of the subtropical high was such that the high level steering current would take the cyclonic system at sea level, away from Tamil Nadu. Investigations by recent workers (*e.g.*, Koteswaram 1967) suggest that the steering concept itself needs to be re-examined from various aspects. However, it will be conceded that the high level data utilised in the present investigation indicate that the steering concept can be depended upon in the Indian area

*The radiosonde, rawin and pilot balloon data over the Indian region were checked against the original scrutinised registers in the India met. Dep. The data over the rest of Asia and over Europe were utilised as received through the northern hemisphere telecommunication channels. They may not therefore be free from mutilations during transmission. In drawing the contours over India at the 200-mb level, much more weightage was given to the winds than to the geopotentials on account of the large errors in the Indian data at this high level.

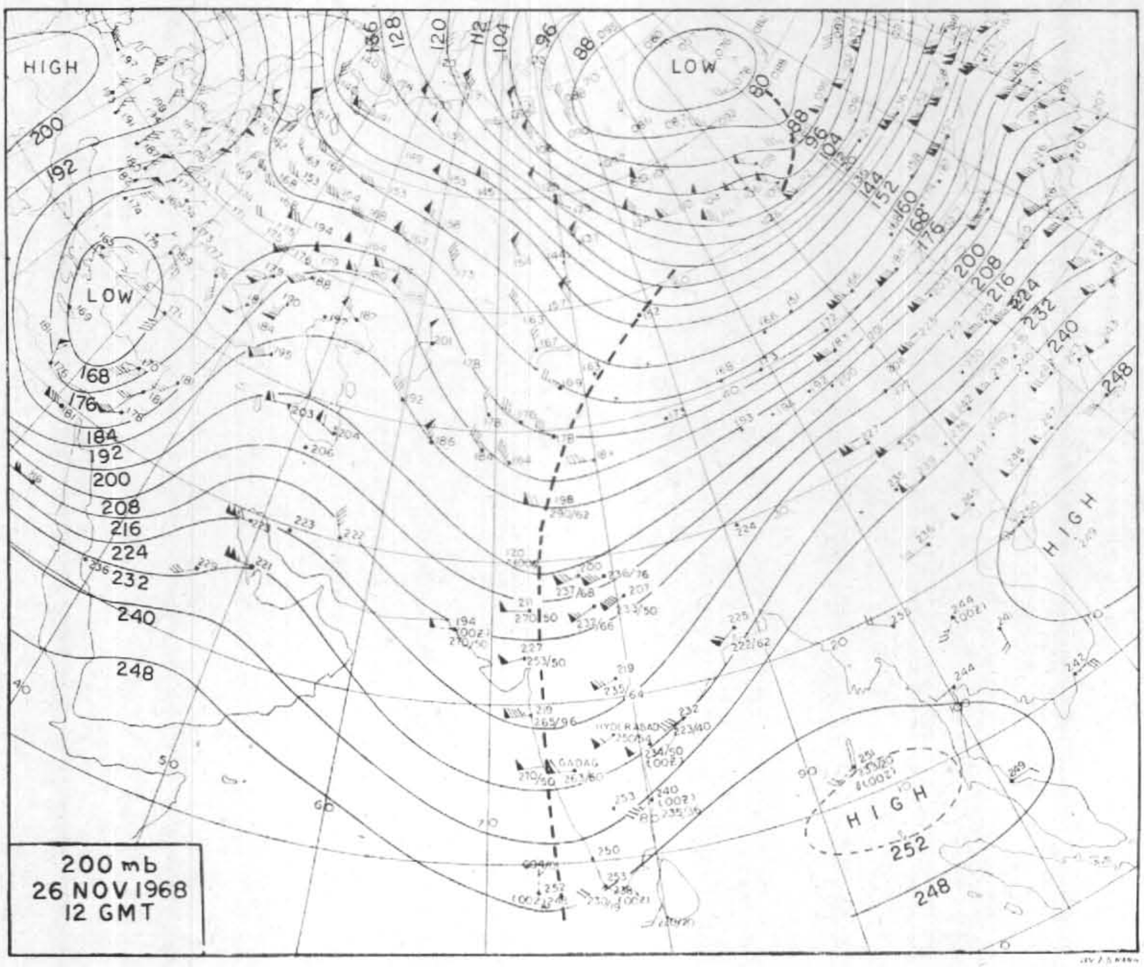

Fig. 8. Convention in plotting is the same as in Fig. 6. Note that the westerly wind is 96 kt at Bombay (19°07′N, 72°51′E) decreasing within a few degrees to the north as well as to the south, to 50 kt. Note also the westerly 60 kt wind over Gadag (15°25N′, 75°38′ E) and the 36 kt southwesterly wind over Madras (13°00′ N, 80° 11′ E) causing an anticyclonic shear of 4·7 m/sec or more per 100 km. Compare the general flow patterns in this diagram with those in Fig. 6 which are for the same date 26 November but in 1966.

until more evidence *to the contrary* becomes available in respect of cyclonic storms in the Bay of Bengal.

Figs. 6 and 7 which depict the 200 mb charts for 26 November 1966 and 10 November 1968 respectively, illustrate* the point explained above. The positions of the centres of cyclonic disturbances at sea level and their directions of movement during the next 24 hours, as published by the India Meteorological Department (1967, 1969) are shown on the respective diagrams.

8. Contrast in daily 200 mb flow patterns over Asia in November 1968 and 1966

The daily 200 mb contour patterns over Asia in November 1968 and November 1966 were very different. The following interesting features deserve special mention.

November 1968 — The month of drought in Tamil Nadu

(*i*) The planetary trough over the Pamirs — the Pamir trough (Flohn 1965) — had large amplitudes. The mean position of the axis of the trough during the month was along 70°E and the mean position of the tip of the trough was at 19°N, *i.e.*, off the coast of Saurashtra. During the second half of the month, when no marked cyclonic disturbances were affecting south or central Bay of Bengal, the westerlies had completely invaded the east Arabian Sea and Peninsular India and the Pamir trough had extended upto 8°N (Minicoy) on a number of days.

(*ii*) In the last 10-day period of the month, jet streams were found embedded in the Pamir trough on a number of days even at Lat. 19°N and winds of 50 kt speed had occurred even at Lat. 14°N.

*Delineation of stream lines at these low latitudes would have brought out the author's point more clearly. The author however preferred not to make a composite analysis with contours to the north of 18°N and streamline analysis in lower latitudes

This aspect will be discussed a little later more in detail.

(*iii*) Except in association with cyclonic storms (*vide* Fig. 2), the core of the subtropical high lay as a closed system over southwest Bay and the adjoining parts of west central Bay and Ceylon.

November 1966-The month of fairly good rainfall in Tamil Nadu

(*i*) The Pamir trough had, in the mean, extended only upto 29°N, *i.e.*, a little to the north of Jacobabad and even in the extreme case, had reached only 23°N, *i.e.*, about 15° further to the north than in November 1968. When the trough extended to latitudes lower than 25°N it had a strong tilt towards the Red Sea and East Africa, *i.e.*, away from the east Arabian Sea and India. The axis of the trough, when it extended from north to south, was, in the mean, along 70°E.

(*ii*) Jet streams were confined on most of the days during the month, to latitudes north of 23°N. They occurred in a confluent region and therefore reached very high speeds.

(*iii*) *The subtropical high dominated the Indian sub-continent, the Bay of Bengal and the east Arabian Sea.* It influenced the region as far west as 60°E in the Arabian Sea, as far east as coastal Burma and as far south as 8°N. The central region of the high lay, in the mean, over northwest and west central Bay of Bengal and the adjoining parts of Peninsular India.

Figs. 6 and 8 show situations representative of the two years 1966 and 1968 and they relate *to the same date of the month*, namely, 26 November. The patterns in the two diagrams are entirely different and illustrate some of the features described above.

9. Contrasts in mean 700-mb contours over the northern hemisphere in November 1968 and 1966

November 1968 was characterised by a considerable weakening of blocking over and near North America and a strengthening of the same in the eastern portion of the northern hemisphere (Stark 1969). According to Stark, a mean ridge which was formerly over Western Europe and the United Kingdom had moved eastward and acquired a strong negative tilt from Greenland to southern Russia and height anomalies increased by 160 m, compared to October 1968, over northern Scandinavia. Stark has also pointed out — to quote his own words—"Amplification spread eastward from the Scandinavian segment of the block. Cold air, confined to the Arctic in October, spread southward in November over western Siberia, *produced the strongest vortex of the month over* the Northern Hemisphere. This resulted in a maximum change" (from October 1968) "of 700 mb height anomaly of about 200 metres and a strong maximum mean wind speed of more than 20 metres per second, west of Lake Baikal." It is relevant to add that the weakening of blocking action over and near North America and the strengthening of the same over the eastern portion of the northern hemisphere, are consistent with the findings of Rex (1950) based on an elaborate investigation on blocking. The developments in blocking in November 1968 pointed out above, are thus well connected anomalies in the general circulation of the atmosphere over the northern hemisphere.

Fig. 9 shows the mean 700-mb contours over Europe and Asia to the north of 30°N in November 1968 as published by Stark.

The deep cyclonic vortex referred to by Stark is *straight to the north of the Indian sub-continent* with its centre near 65° N, 85°E. The closed isopleth of mean maximum wind speed of 20 m/sec at the 700-mb level as published by Stark (not reproduced) lies between 70°E and 80°E. The *mean* maximum speed in this area at the 300-mb level must have been very much higher. This aspect is discussed in greater detail in a later section.

The above picture is very different from that seen in Fig. 10 which shows the mean 700 mb contours over Europe and Asia to the north of 30°N in November 1966 (Wagner 1967). In this diagram, we see a closed low with its centre near 65°N, 140°E, *i.e.*, *at the same latitude* as the deep vortex in November 1968 *but 55 degrees further to the east.* The flow of westerlies between 40°N and 30°N to the north of India is also much weaker* in November 1966 than in November 1968.

The contrasts in the mean flow patterns over Europe pointed out above are consistent with the findings of Rao (1963) based on Hovmöllers' diagrams for 1949 and 1946.

10. The sub-polar vortex and polar front jet streams and their "impact" on the sub-tropical jet stream system over India

In order to find out how the subpolar vortex and intense polar front jet streams reacted on the STJS over India, the daily 300 and 200-mb charts at 00 and 12 GMT in November 1968 were examined. The daily positions of the centre of the subpolar vortex at 00 GMT at 300-mb level and

*Figs. 9 and 10 are reproductions from portions of northern hemisphere charts published by Stark and Wagner respectively who belong to U.S. Weather Bureau. The mean contours have been delineated in the U.S. Weather Bureau charts in metres in Nov. 1968 and in feet in Nov. 1966. This may cause some difficulty to the reader in comparing the gradients in Figs. 9 and 10. But this is unfortunately unavoidable.

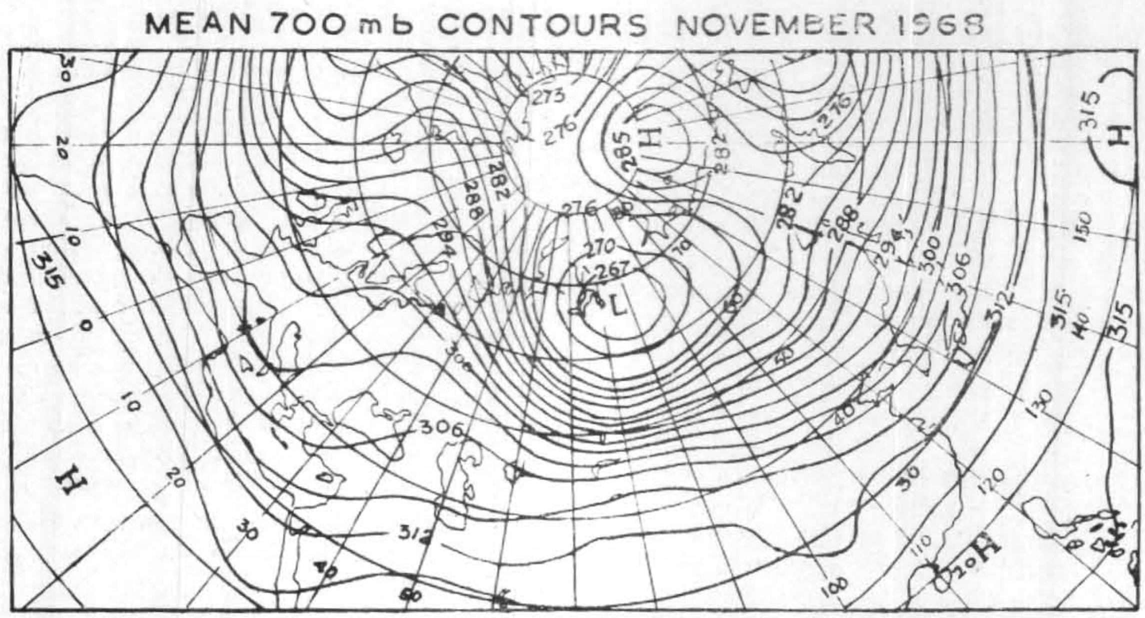

Fig. 9. Contours drawn at intervals of 30 m. Note the pronounced ridge over Scandinavia. Note the deep cyclonic vortex marked L and the intense jet stream (as seen from the spacing of the contours) with its core near 50°N in the longitude-range 70°E to 100° E. Note also the strong westerlies south of 40°N and between 70°E and 100° E, as seen in the number of contours. Compare the patterns in the corresponding areas in Fig. 10.

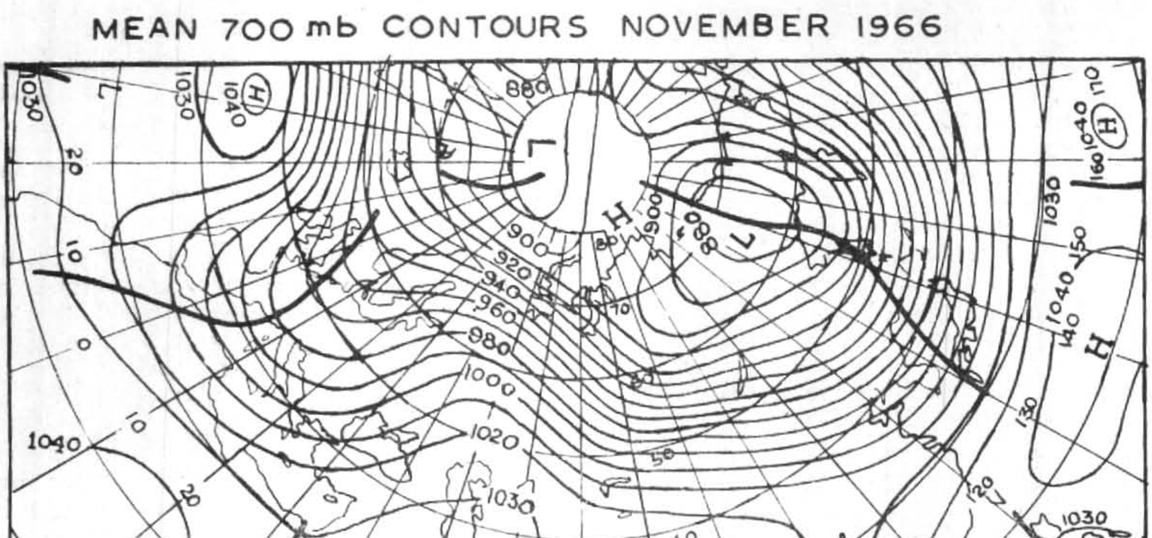

Fig. 10. Contours drawn at intervals of 100 ft. Compare the patterns in the corresponding areas in Fig. 9.

the cores of the jet streams between 70°E and 80°E (*i.e.*, along the mean longitude of 75°E) on the basis of the 300 and 200-mb level charts were determined. The cores were identified by visual examination of the direction and speed of the winds as plotted on charts. The mean longitude of 75°E, was selected because the maximum number of wind observations were available in the longitude range 70°E to 80°E, between Lat. 5°N and 70°N. The method based on visual examination was preferred to the conventional method of preparation of atmospheric cross-sections as it involved much less labour. Though, however, it made the analysis a little more subjective, this simplification in the procedure, at a slight expense of accuracy, was of little consequence for the purpose we had in view.

The following are some of the special features of the subpolar vortex and the jet stream systems besides those seen in Tables 2 and 3.

(*i*) The mean position of the centre of the subpolar cyclonic vortex at 00Z was 68°N, 90°E at the 300-mb level. This position is consistent with the 700 mb position as seen in Stark's diagram *vide* Fig. 10. Its extreme positions were Lat. 62°N & 75° N and Long. 60°E & 120°E.

(*ii*) There were two polar front jet streams. We shall refer to the one in the higher latitude as PFJ_1 and the other as PFJ_2. These jets are best seen at the 300-mb level. PFJ_1 was observed on the upper air charts throughout the month and it could be identified without any difficulty. PFJ_2 could however be seen as a definite entity only on 20 days in the month. It was distinctly weaker than PFJ_1 and one could perhaps even consider it on some days as only a wind maximum without the lateral shear characteristic of a jet stream. Further, it occasionally moved southwards and merged with STJ over India. For example, it merged with STJ on 23 November 1968 and thereafter, it was difficult to locate it as a separate entity till the end of the month. Incidentally, it may be noted that the chart for 200-mb level for 26 November 1968 reproduced in Fig. 8 does not show any separate PFJ_2. The PFJ_1 is seen as a separate entity in much higher latitudes. It is seen much better at the 300-mb level. It is relevant to add that the existence of a second polar front jet, its entry into India on some occasions in February 1967 and the consequent intensification of STJ have been recently pointed out by Singh (1971).

(*iii*) In association with blocking over Scandinavia, the deep cyclonic vortex V occasionally bulged into troughs towards India. The protrusion of these troughs resulted in intensification of PFJ_2 when it existed as a separate entity and, in its absence, the westerlies to the south of the trough became stronger. A good instance of intensification of PFJ_2 by a protruding trough from PFJ_1 may be seen in the charts for 8 November 1968 (not reproduced in our paper). Likewise, the PFJ_2 embedded in a trough and moving equatorward, intensified STJ. The intensification of STJ by 00 GMT of 20 November 1968 (charts not reproduced) is a typical instance supporting our viewpoint. These observations of ours are consistent with the fact already known that deeply penetrating cold air outbreaks in U.S.A. lead to wind speed maxima (Reiter 1963).

(*iv*) The interesting features in the subtropical jet stream system were —

(*a*) After 20 November 1968, a westerly jet core was found over Peninsular India near about 19°N on a number of days. This core which we shall refer to as the secondary STJ, was in addition to the one which was near about 25°N, in the mean, throughout the month. The secondary STJ was associated with a lateral shear of 4·4 to 6·5 m/sec/100 km and with wind speeds varying between 70 and 95 kt. Fig. 8 contains one such example of a secondary STJ. It will be seen from the diagram that the wind was 95* kt at Bombay (19°07′ N, 72°51′E) and 50*kt at Vengurla (15°52′N, 73°38′ E) which is at a latitudinal distance of 360 km to the south of Bombay. This works out to an anticyclonic shear of 6·5 m/sec/100 km. The cyclonic shear to the north of Bombay works out to 4·9 m/sec/100 km on the basis of the 50 kt wind over Ahmadabad (23°04′N, 72°38′E).

(*b*) Wind speeds of 60 kt or more had occurred over Peninsular India even at the latitude of 15°N as pointed out in an earlier section. The wind speed decreased to low values on the equatorward side of "wind maximum". However, it appeared from the available observations that the lateral shear in these cases might not have reached the high values for a *jet*.

Table 2 shows the mean latitudinal positions of the centre of the subpolar vortex V, the cores of PFJ_1, PFJ_2 and STJ and the extreme positions occupied by these systems in November 1968. The table also contains similar data in respect of the lowest latitudes over India where westerly winds reached 60 kt or more in November 1968. The last mentioned data were based either on the actual wind observations over those very latitudes (within half a degree) or they were determined by interpolation from wind observations at the nearest stations on either side of the latitudes concerned, *provided the actual winds on either side had reached 50 kt or more.* We shall refer to the lowest latitudes of "maximum wind" of 60 kt as LLMW hereafter. The error involved in these determinations is estimated to be about one degree and will not, in any case, exceed two degrees of latitude. This degree of accuracy is considered good enough for the purpose for which we have presented the table.

It is interesting to note from Table 2 that the latitudinal differences between the extreme positions of V, PFJ_1, STJ, LLMW are nearly the same in all the cases. This may not be due to mere chance.

*As stated in a previous section of this paper, all Indian data are checked-data taken from scrutinised registers.

TABLE 2

System	Mean position during Nov. 1968	Extreme latitudinal positions			Special remarks
		Highest	Lowest	Difference	
Subpolar vortex V	68°N	75°N	62°N	13°	—
Core of PFJ_1	54°N	60°N	48°N	12°	—
Core of PFJ_2	38°N	41°N	34°N	7°	Merged with STJ on 10 days in the month in different spells.
Core of STJ	25°N	29°N	19°N	10°	—
LLMW (*Lowest* latitude of 60 kt wind over India)	21°N	26°N	15°N	11°	—

TABLE 3

System	Frequency of days during the period of Nov, 68		
	1-10	11-20	21-30
V in its southernmost 5-degree range (62°-66°N) : number of days	0	2	9
PFJ_1 in its southernmost 5-degree range (48-52°N) : number of days	0	4	6
STJ in its southernmost 5-degree range (19°-23°N)	0	2	6
LLMW in its southernmost 5-degree range (15°-19°N)	0	4	10
Dep. from normal (%) of 24-hr rainfall over Tamil Nadu during the 10-day period	—7 (84·4)	—48 (38·2)	—61 (23·8)

Figures in bracket indicate actual rainfall (mm) in 10-day period

With regard to PFJ_2, it may be stated that this system was not a persistent feature throughout the month *vide* earlier comments on the characteristics of this system and also remarks in Table 2. We need not therefore compare the characteristics of this system with those of the other 4 systems described above.

Table 3 shows the number of days during the period 1-10, 11-20 and 21-30 in November 1968 when each of the 4 systems V, PFJ_1, STJ and LLMW lay within 5 degrees of the southernmost position reached by them respectively. The table also contains for purposes of comparison,

(*i*) The total daily rainfall over Tamil Nadu, *as a whole*, during the same 10-day periods. These figures are given within brackets below the respective percentage departures from normal (*see* sub-para below).

(*ii*) The departures from normal of the total daily rainfall over Tamil Nadu, *as a whole* in the 10-day periods, expressed as percentages.

It will be seen from Table 3 and Fig. 11 that all the four systems showed a trend, in the mean, to migrate to lower latitudes with the progress of the month. The associations between V and PFJ_1, between PFJ_1 and STJ and between STJ and LLMW have been vividly brought out by Table 3 and Fig. 11. It is also interesting to observe that *the negative percentage departure from normal of the rainfall over Tamil Nadu progressively increases during the succesive 10-day periods as all the systems (namely, V, PFJ_1, STJ and LLMW) migrate progressively towards lower latitudes.* The similarity in the trend af all these curves may not be due to mere chance. On the other hand, one is tempted to infer on a quasi-empirical basis that the *flow patterns in the upper troposphere, apart, of course, from other important factors in the lower and/or the middle troposphere, e.g., lack of convergence below the "level of non-divergence" may have inhibited rainfall, progressively after 10 November 1968.*

With regard to PFJ_2, we have not included any statistics in Table 3 for the reasons already pointed out. However, the available evidence clearly shows that PFJ_2 acted as an intermediary between PFJ and STJ. The PFJ_1 in its equatorward movement, energised PFJ_2 and the latter, in its turn, moved southward, "shifted" STJ and LLMW further equatorward and energised the subtropical jet stream system.

Thus our investigations have revealed a *series of links in the atmospheric processes, each one of which is well connected with the following one and, in some cases, with one or two later links also. The links begin with the blocking over and near the United States of America and end with the severe drought over Tamil Nadu.* These links are described briefly in the following section on general conclusions. It need hardly be added that the study of more cases of this type would help to confirm the existence of similar teleconnections between monsoon developments over India and atmospheric circulation in distant parts of the globe.

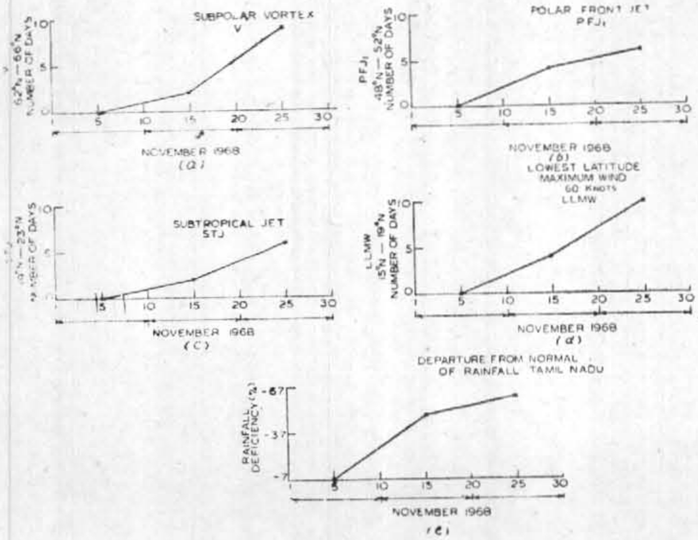

Fig. 11. Note the similarity in the trend of all the curves in the diagrams 5(a) to 5(e)

11. General Conclusions

Based upon the above synoptic study, we arrive at the following quasi-empirical general conclusions —

(*i*) During the drought month of November 1968, there were certain remarkable developments in subpolar and middle latitudes to the north of the Indian sub-continent, which were themselves associated with anomalies in the general circulation of the atmosphere which could be traced back as far west as the United States of America. A powerful surge of cold air from the Arctic led to the development of a very deep cyclonic vortex in subpolar latitudes and an intense polar front jet stream to the south of this vortex. Troughs of large amplitudes which occasionally developed in this vortex in association with persistent and pronounced blocking over Scandinavia led to invasion of cold air and transfer of energy from the above mentioned polar front jet stream to other systems in lower middle latitudes, the subtropics and even to latitudes further south in India. The deep subpolar vortex, the polar front and subtropical jets and the latitude of wind maximum of 60 kt further to the south also showed a progressive trend to shift equatorward with the advance of the month after 10 November. These factors led to a marked intensification of the subtropical jet stream system over India and its occupying, in the mean, an unusually low latitudinal position.

(*ii*) The change in the mean position of the subtropical jet stream system affected the flow patterns at all levels between 850 and 200-mb levels over the Indian sub-continent.

(*iii*) The perturbations associated with the STJS in its new position shifted the subtropical high to abnormal positions and "forced" it to have abnormal configurations at the 200-mb level. These anomalies in the subtropical high, in their turn, were responsible for the cyclonic storms in the Bay of Bengal being "steered away" from Tamil Nadu, during the first fortnight and were thus also partly responsible for the drought conditions in that State. Further, on account of the perturbations in the STJS, the planetary Pamir trough extended at the 200-mb level into the east Arabian Sea as far south as 8°N and the subtropical high shifted into the southwest Bay and Ceylon, progressively during the last three weeks. It is possible that these unusual upper tropospheric flow patterns, apart, of course, from other important factors in the lower and/or middle troposphere, inhibited rainfall progressively during this three-week period and thereby aggravated the rainfall deficiency over Tamil Nadu.

(*iv*) There was little difference between the moisture content of the air over Tamil Nadu during November 1968, the drought-month and in November 1966, the month of fairly good rainfall. It was the absence of adequately potent mechanisms to lift the available moist air to the appropriate levels, which led to the drought.

(*v*) The meteorological parameters utilised in our present study of opposite types of synoptic situations may be useful in the application of the JR technique (Ramaswamy 1968) for the medium-range forecasting of rainfall over Tamil

Nadu during the retreating monsoon period. It therefore appears worthwhile to try out MRF for Tamil Nadu by utilising the parameters presented in this paper.

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REFERENCES

Flohn, H.	1965	W.M.O. Tech. Note, 66, p. 1.
India met. Dep.	1967	*Indian. J. Met. Geophys.*, **18**, 2, pp. 293-298.
	1969	*Ibid.*, **20**, 2, pp. 155-160.
Jagannathan, P. and Ramamurthi, K. M.	1963	*Aust. Met. Mag.*, **41**, p. 42.
Koteswaram, P.	1953	*Indian J. Met. Geophys.*, **4**, 1, pp.13-21.
	1967	*Mon. Weath. Rev.*, **95**, 8, pp. 541-564.
Ramaswamy, C.	1956	*Geophysica.*, **6**, 3-4.
	1968	Prince Mukarram Jah lectures, 1967, pp. 94-96.
	1969	*Cur. Sci.*, **38**, 3, pp. 53-58.
Rao, K. V.	1963	*Indian J. Met. Geophys.*, **14**, 2, pp. 143-155.
Rao, P. R. Krishna	1953	*Mem. India met. Dep.*, **30**, 1, pp. 16-17.
Rao, P. R. Krishna and Jagannathan, P.	1953	*Indian J. Met. Geophys.*, **4**, 1,pp. 22-44.
Reiter, Elmar R.	1963	*Jet-stream Meteorology*, Univ. Chicago Press, pp. 1, 224-229.
Rex, Daniel F.	1950	*Tellus*, **2**, 4, pp. 279, 282
Singh, M. S.	1971	*Indian J. Met. Geophys.*, **22**, 1, pp. 1, 149.
Stark, L. P.	1969	*Mon. Weath. Rev.*, **97**, 2, pp. 89-97.
Thiruvengadathan, A.	1965	*Indian J. Met. Geophys.*, **16**, 1, pp. 61-68.
Wagner, James A.	1967	*Mon. Weath. Rev.*, **95**, 2, pp. 89-97.