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Monsoon variability in relation to equatorial trough activity over Indian and West Pacific Oceans

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सार – अन्तर्राष्ट्रीय तिथि रेखा के पश्चिम में प्रशान्त महासागर और हिन्द महासागर के ऊपर भूमध्यरेखीय द्रोणी की सहवनी संक्रियता से सम्बन्धित भारतीय मानसून वर्षा (अन्तर वार्षिक और अन्त : ऋतुनिष्ठ दोनों) का परीक्षण किया गया है। यह पाया गया है कि पश्चिम प्रशान्त भूमध्यरेखीय द्रोणी के निकट चक्रवात जनन (उष्णकटिबन्धीय चक्रवात) 30-50 दिनों की अवधि में इस महासागर बेसिन और उत्तरी हिन्द महासागर के बीच संवहन में ढेकुली के द्वारा इस परिवर्तन से सम्बन्धित है। उत्तरी हिन्द महासागर और पश्चिम प्रशान्त महासागर के ऊपर समुद्र सतही ताप (SST) असंगतियां, मानसून के आरम्भ की तारीख में परिवर्तन और 30-50 दिन मोड द्वारा भारत पर मानसून वर्षा की मात्रा का भी कारण बन सकती है।

ABSTRACT. Variability of Indian monsoon rainfall has been examined in relation to the convective activity of the equatorial trough over the Indian Ocean and the Pacific Ocean west of the International Date Line. It is found that the cyclogenesis (tropical cyclones) near the West Pacific equatorial trough is closely related to this variability through a see-saw in convection between this ocean basin and north Indian Ocean, with period in the range 30-50 days. SST anomalies over north Indian Ocean and West Pacific Ocean can cause variability of the date of onset of monsoon and also the quantum of monsoon rainfall over India through the 30-50 day mode.

1. Introduction

Monsoon has large interannual variability (*i*) in the quantum of monsoon rainfall over India from 1 June to 30 September and (*ii*) in the date of onset of monsoon rains. Monsoon has also large intraseasonal variability. Active-break cycle was known since long. During the last decade there have been many studies on the 30-50 day mode of the monsoon. In this paper these variabilities are examined in relation to the convective activity associated with the Equatorial Trough (ET) in the Indian Ocean and in the Pacific Ocean west of the International Date Line.

2. Monsoon, onset, over Kerala (MOK)

2.1. The climatological date of onset of monsoon over the southernmost State of India, Kerala (MOK), is close to 1 June. Over the last 100 years monsoon onset dates have varied from 11 May in 1918 to 18 June in 1972. Examination of the Sea Surface Temperature (SST) data has shown that beginning in early April, tropical north Indian Ocean and adjoining West Pacific warms rapidly in the annual cycle and by the end of May, a large oceanic area from about 60° E to 120° E north of the equator attain temperatures above 30° C, which becomes the warmest tropical ocean area then. Large moisture convergence will then result over this warmest ocean area, which in turn builds up a huge heat source in the troposphere over south Asia, making large changes in the temperature and wind fields. This scenario fits in to the description of the onset of monsoon. After this event north Indian Ocean is cooled by the strong monsoon westerlies and from June to September the climatological warmest about 29° C ocean area is found between 110° E and 160° E. Fig. 1 gives the SST isotherms over the area during May as an average for the period 1961-1970.

2.2. Fig. 2 taken from Joseph and Pillai (1987) shows composite SST (Voluntary Observing Fleet data) over 5-degree latitude-longitude squares for the week just before the week containing MOK during the period 1961 to 1972. The previous week also shows high SST over east central Arabian Sea. This is the place where 'Onset Vortex' heralding MOK generally forms.

2.3. Ananthakrishnan and Soman (1988) have derived dates of MOK for each year of the period 1901 to 1980 using rainfall data and well defined criteria for the monsoon onset. For south Kerala they used mean daily rainfall derived from a network of 44 raingauge stations. The decade 1901-1910 had a mean date of MOK of 4 June while for the decade 1951-1960 it was 24 May. It is interesting to note that the decade 1951-1960 had the highest SST in the ET region of the north Indian Ocean during the period and the decade 1901-1910, the lowest (Shukla 1987).

2.4. Table 1 shows the decadal mean of MOK (south Kerala) for the period 1901-1980, using onset dates as derived by Ananthakrishnan and Soman (*loc. cit*). The climatic change in the date of MOK during the current century as may be seen from the table is very significant. If a ten-year moving average is taken the

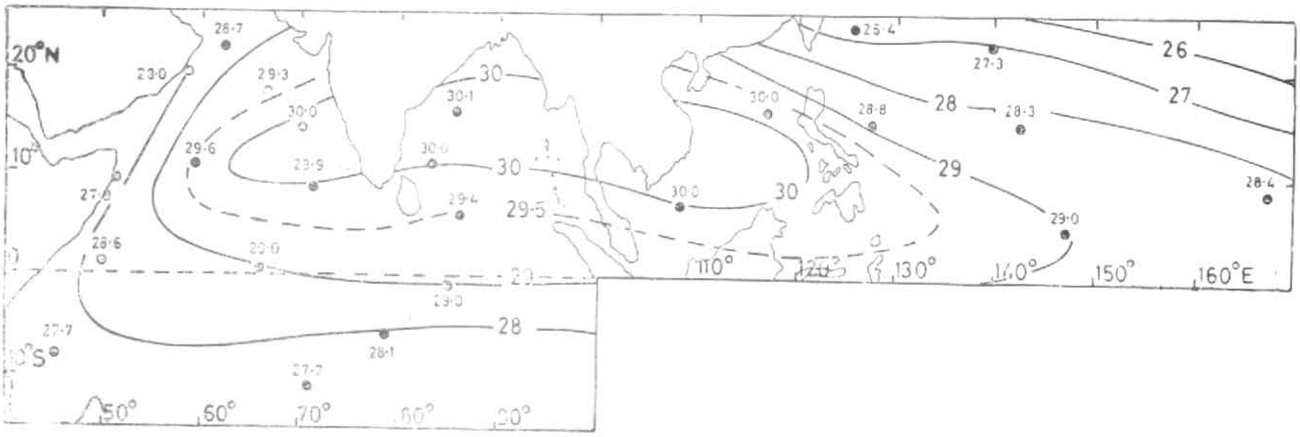

Fig. 1. SST, May (1961-1970)

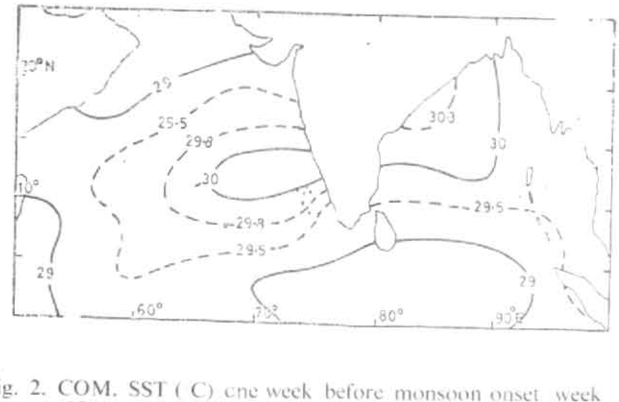

Fig. 2. COM. SST (°C) one week before monsoon onset week (1961-1972)

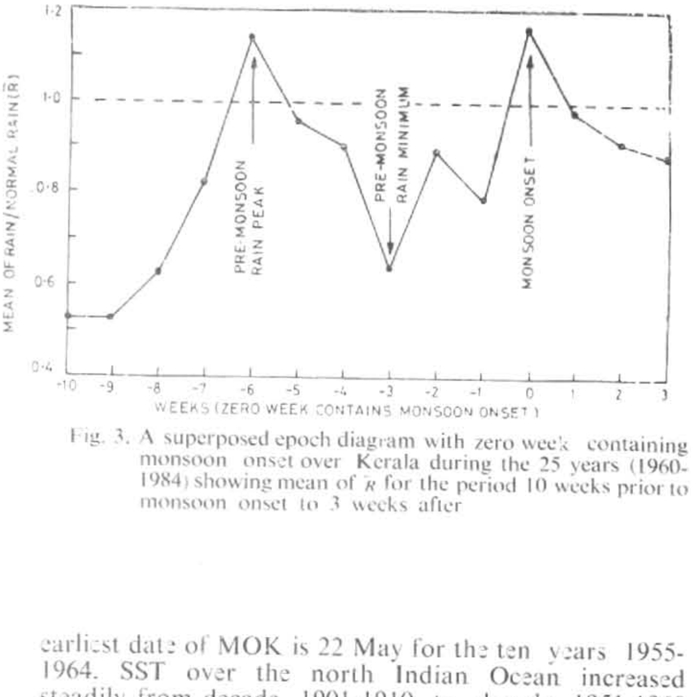

Fig. 3. A superposed epoch diagram with zero week containing monsoon onset over Kerala during the 25 years (1960-1984) showing mean of $\bar{R}$ for the period 10 weeks prior to monsoon onset to 3 weeks after

TABLE 1

Decadal means of dates of monsoon onset over south Kerala 1901-1980 (dates of MOK as derived by Ananthakrishnan and Soman 1988)

Decade	Decadal mean date of monsoon onset over south Kerala	Decade	Decadal mean date of monsoon onset over south Kerala
1901-1910	4 June	1941-1950	27 May
1911-1920	29 May* (1 June)	1951-1960	24 May
1921-1930	1 June	1961-1770	28 May
1931-1940	31 May	1971-1980	1 June

*There is a very early date of MOK during the decade 1911-1920 of 7 May in 1918. If this is taken as PMRP then MOK will be on 14 June and the decade mean 1911-1920 will be 1 June, as given in brackets.

earliest date of MOK is 22 May for the ten years 1955-1964. SST over the north Indian Ocean increased steadily from decade 1901-1910 to decade 1951-1960 and thereafter decreased as may be seen from Shukla (*loc. cit*). As may be seen from Table 1, dates of MOK also had a parallel variation except for the decade 1911-1920. The mean of this decade is low due to a single year 1918 which had a MOK on 7 May. It will be seen from Sec. 3 that rainfall over Kerala is affected by the 30-50 day mode. From Fig. 2 of Ananthakrishnan and Soman it is seen that MOK during this year can be taken as 14 June if the next spell of increased rainfall is taken as MOK which will make this decadal mean 1 June.

3. Pre-monsoon rain peak (PMRP)

3.1. Studying the weekly rainfall index (as defined in their paper) which represents spatial mean rainfall of the four meteorological sub-divisions Arabian Sea

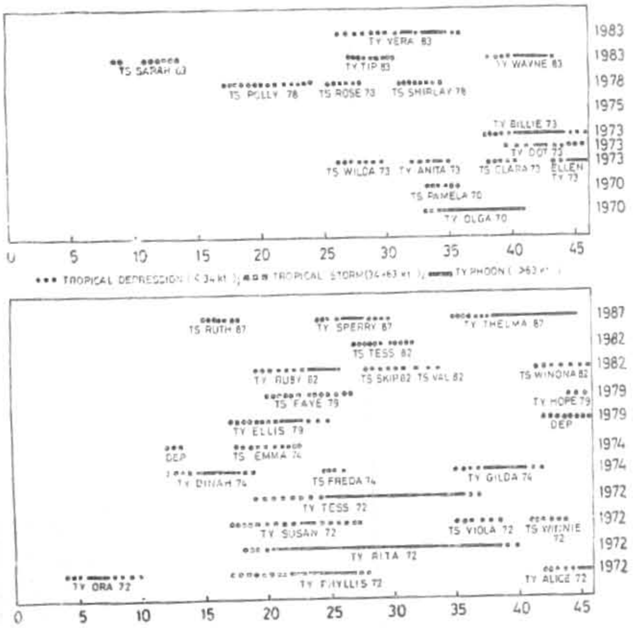

Fig. 4. Time duration of tropical cyclones over West Pacific north of the equator with respect to date of MOK taken as zero for 0 to 45 days for 5 years each of EMR and DMR

TABLE 2

Data in respect of EMR years

Years of excess monsoon rainfall (EMR)	Monsoon rainfall of India (in mm)	Date of monsoon onset over Kerala (MOK)	Date of pre-monsoon rain peak (PMRP)
1970	939	26 May	12 Apr
1973	912	4 Jun	22 Apr
1975	960	31 May	27 Apr
1978	908	28 May	9 Apr
1983	955	13 Jun	1 May
Mean	935		

TABLE 3

Data in respect of DMR years

Years of deficit monsoon rainfall (DMR)	Monsoon rainfall of India (in mm)	Date of monsoon onset over Kerala (MOK)	Date of pre-monsoon rain peak (PMRP)
1972	653	18 Jun	7 May
1974	747	26 May	14 Apr
1979	708	11 Jun	5 May
1982	735	1 Jun	18 Apr
1987	688	2 Jun	26 Apr to 3 May (Flat peak)
Mean	706		

Islands, Kerala, Tamil Nadu and Bay Islands in the latitude belt 8° N to 13° N, between longitudes 70° E and 90° E, for the years 1960 to 1984, Joseph and Pillai (1988) found that a peak in rainfall activity similar to that at monsoon onset time occurs in these sub-divisions about six weeks before the onset of monsoon over Kerala in almost all these years. Taking the date of MOK counted in days from 1 April as Y and the date of Pre-Monsoon Rain Peak (PMRP) counted from the same 1 April as X, it is found that the linear correlation coefficient between X and Y is 0.87, which is statistically highly significant. The linear regression equation between X and Y is obtained as $Y = 0.75X + 46.19$. Thus, during the period April to June there are two spells of increased activity for the ET, of which the latter is the one associated with MOK.

3.2. Yasunari (1980) and Sikka and Gadgil (1980) have shown that the monsoon season, June to September is characterised by a northward propagating low frequency mode in cloudiness of period 30-50 days. Using FGGE MONEX wind data of 850 mb level Krishnamurti and Subramanyam (1982) found that the 30-50 day mode existed in 1979 even in May, prior to the onset of monsoon over Kerala. MOK and the PMRP could, therefore, be identified as manifestations of this mode of the tropical atmosphere.

3.3. Joseph and Pillai (1988) used their weekly rainfall index ($\bar{R}$) series to obtain a mean picture of the temporal changes in the rainfall over the east-west belt 8° N-13° N before the MOK. Superposed epoch method was used. The week containing MOK was taken as the zero week. Mean of $\bar{R}$ for 25 years (1960-1984) for weeks, 10 to 3 are shown in Fig. 3. The rainfall peaks corresponding to MOK and PMRP are clearly seen. PMRP is on the average 6 weeks prior to MOK. Rainfall activity in the area covered by the four sub-divisions, *i.e.*, Arabian Sea Islands, Kerala, Tamil Nadu and Bay Islands is a minimum 3 weeks prior to MOK.

4. Tropical cyclones of West Pacific Ocean

4.1. Tropical West Pacific Ocean generates 26 out of the 79 tropical cyclones produced by global oceans in a year (Gray 1978). About 60 per cent of these occur during the four months (June-September) when India gets its summer monsoon rainfall. Many of these reach typhoon and super-typhoon intensities. There have been very few studies regarding the interaction between these tropical cyclones and the Indian monsoon. The tropical cyclone activity in western North Pacific Ocean was examined in relation to the convective activity of the north Indian Ocean. It is known that both these areas have a prominent 30-50 day signal in many parameters of the atmosphere and the ocean. PMRP and MOK are manifestations of this mode in rainfall associated with the ET over north Indian Ocean. Two groups of years were chosen, each containing 5 years from the period 1970-1987. The first group has years with Excess Monsoon Rainfall (EMR) over India and the second group with Deficient Monsoon Rainfall (DMR). The average monsoon rainfall (1 June to 30 September) of India for each year was used for the purpose. Tables 2 and 3 give required details regarding these years. EMR years have the highest

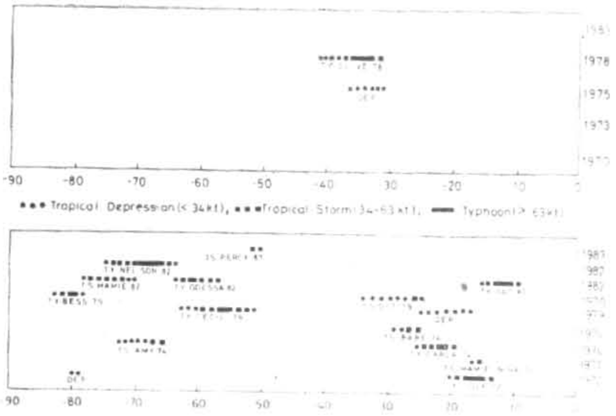

Fig. 5. Time duration of tropical cyclones over West Pacific Ocean, north of the equator with respect to date of MOK taken as zero for 0 to 90 days fo 5 years each of EMR and DMR

rainfall during the 1970-1987 period and DMR years the lowest. Two long term mean (normal) rainfall of India as derived by them is 853 mm with a standard deviation of 83 mm.

4.2. Tropical cyclone data was collected from the Annual Tropical Cyclone Reports published by the Joint Typhoon Warning Centre (JTWC), Guam. Fig. 4 gives the tropical cyclone duration data over West Pacific (west of the International Date Line and north of the equator) plotted against number of days counted from MOK which is taken as the zero day for each year. Depression, tropical storm and typhoon stages are marked with different symbols as shown in the figure. The following broad inferences could be drawn from Fig. 4, neglecting the isolated cases of tropical cyclogenesis (formation of depression, tropical storm or typhoon) :

(a) In EMR years, cyclogenesis does not occur during the first four weeks after MOK. In contrast in DMR years only the first two weeks are free from cyclogenesis.

(b) In both the EMR and DMR years cyclogenesis once started continues till the end of 6 weeks.

(c) Typhoon days are many times more in DMR year than in EMR years.

4.3. Fig. 5 gives similar data for a period of 90 days before MOK, which covers the PMRP also. The following inferences could be drawn :

(a) Cyclogenesis does not occur close to the dates of MOK.

(b) Coyclogenesis does not also occur around the days of PMRP.

(c) The 90-day period studied covers two 30-50 day cycles. The difference in cyclogenesis between DMR and EMR years is considerable; there is hardly any cyclogenesis in EMR years.

TABLE 4

The monthly mean SST in °C at representative points along the ET zone in north Indian Ocean and West Pacific Ocean

Location	Jan (Jul)	Feb (Aug)	Mar (Sep)	Apr (Oct)	May (Nov)	Jun (Dec)
Indian Ocean (10-12°N, 81-84°E)	26.7 (28.8)	26.9 (28.4)	28.2 (28.5)	29.5 (28.6)	30.0 (28.1)	28.9 (27.4)
West Pacific (4-6°N, 145-150°E)	28.6 (29.1)	28.6 (29.1)	28.5 (29.3)	28.8 (29.4)	29.0 (29.1)	29.2 (29.0)

5. Mechanism for the 30-50 day mode

5.1. A possible mechanism for the 30-50 day mode involving the tropical areas of the north Indian Ocean and the North Pacific Ocean west of the International Date Line is proposed. The entire area has a flat SST field, equator to 15° N, during March to November, when 30-50 day mode is active as may be seen from Table 4. From the cloud pictures given by INSAT-1B (Indian Geostationary Satellite at 74°E) of the years 1984-1988 showing active convective areas and data on tropical cyclones over the area, the following picture emerges. ET becomes active over equatorial Indian Ocean and the active convective cloud band formed there slowly moves north towards the Himalayas (Sikka and Gadgil 1980) leaving the Indian Ocean area cloud free. At this stage West Pacific ET becomes convectively active and it also generates depressions, tropical storms, typhoons and even super-typhoons. After an interval of 30-50 days the process gets repeated. Enhanced activity around the equatorial trough can reduce SST (Joseph and Pillai 1987) and also conditional instability of the tropical atmosphere there. During the inactive periods of ET, SST and conditional instability of the atmosphere can increase due to solar radiation and ET become again active. There could thus be a see-saw in convective activity between these two ocean basins. Since, by the end of May, SST is warmest over north Indian Ocean due to the seasonal march of the sun and the properties of the upper ocean layer, active convection sets in over this ocean basin then, which brings about the monsoon onset over Kerala with a standard deviation of only 8 days (Ananthakrishnan and Soman 1988). This is taken as a phase locking of the 30-50 day mode phenomenon to the monsoon onset over Kerala.

5.2. When the West Pacific ET zone becomes active the strong Walker and Hadley cells generated can increase surface pressure over central India (positive pressure departures) and increase the strength of the Australian Surface Pressure High (ASPH). When the reverse occurs, pressure departures over central India are negative and ASPH has much lower pressures. Upper tropospheric circulation also experience considerable changes in response to the changed location of the convective heat sources. Atmospheric conditions over India during periods of intense convection in West Pacific fits in well with the observed characteristics during weak/break monsoon spells.

TABLE 5

Some of the elements of the sea-saw in convection between north Indian and West Pacific Oceans during April to July 1986

Period	Tropical cyclones of West Pacific and convection in N. Indian Ocean	Central pressure of Australian surface pressure high
24 Apr-3 May	(1) Typhoon *Ken*, 24 Apr-3 May	Very high
4-14 May	No West Pacific cyclones but convective activity high over north Indian Ocean	Near normal
15-29 May	(2) Super typhoon. *Lola* 15-23 May	Very high
	(3) Tropical storm, *Mac*, 22-29 May	
30 May-19 Jun	No West Pacific cyclones but convective activity high over north Indian Ocean	Near normal
20 Jun-17 Jul	(4) Typhoon, *Nancy*, 20-25 Jun	Very high
	(5) Tropical storm, *Owen*, 26 Jun-2 Jul	
	(6) Super-typhoon, *Peggy*, 28 Jun-11 Jul	

5.3. Examination of the results of the study by Krishnamurti and Subramanyam (1982) is relevant here. They analysed 850 mb wind field of the FGGE MONEX period and obtained east-west oriented troughs and ridges moving south to north at a speed of roughly 0.75° latitude per day, with a meridional wave length of about 30 degrees of latitude and period in the range 30-50 days. It is important to note following : (*i*) alternate passage of troughs and ridges is shown to produce pressure fluctuations of the order of 2 to 3 millibars over central India, (*ii*) on careful examination of their trough-ridge diagrams of 1979 (May to September), it is seen that the troughs have a length scale less than 60 degrees of longitude, which means that at a time, the area of active convection has east-west extent limited to 60 degrees of longitude. Both these fit well with the proposed model for 30-50 day mode over Indian and West Pacific Oceans.

5.4. Further support is obtained from the analysis of data in respect of 1986, a year when monsoon rainfall was deficient. The year thus belongs to the DMR years. Data in respect of the tropical cyclones of April to July 1986 is given in Table 5. It is seen that there are 3 periods of active cyclogenesis over the West Pacific Ocean Basin : 24 April to 3 May, 15 May to 29 May and 20 June to 17 July. INSAT-1B pictures were examined to find out the periods of intense convection in north Indian Ocean. It is found that they fit into the time slots in between the cyclone spells.

5.5. Table 5 shows some of the components of the see-saw in convection between north Indian Ocean and West Pacific Ocean. Time flows from up the diagram downwards. During the period 24 April to 3 May of cyclogenesis in West Pacific, ASPH had central pressures as high as 1036 mb. Again during the similar periods of cyclogenesis of 15 May to 29 May and 20 June to 17 July, ASPH had central pressures as high as 1034 mb and 1030 mb respectively. During these two periods, pressures over central India were above normal by 4 to 6 millibars. In the periods in between, central pressures of ASPH were much lower and central India had below normal pressures.

5.6. Cloud bands over Indian Ocean during May and June 1986 had systematic northward movement but they hardly showed any eastward displacement. ET cloud bands over West Pacific were found to form *in situ* and then generate tropical cyclones. INSAT pictures also showed that ET cloudbands of north Indian Ocean did not extend into the West Pacific Ocean and *vice-versa*. It appears that the ET cloudband has a preferred length scale of 40 to 60 degrees of longitude.

6. Discussion of results

(a) MOK by the end of May is due to the rapid seasonal warming of north Indian Ocean resulting in the area becoming the warmest ocean area which invites large scale moisture convergence that builds up a huge heat source in the atmosphere there. A corollary of this is that SST anomalies over Indian and Pacific Oceans are related to the variability of the dates of onset of monsoon.

(b) Convective activity over north Indian Ocean and cyclogenesis over West Pacific Ocean north of the equator are componets of the 30-50 day cycle observed over these areas. When Indian Ocean is convectively active, West Pacific Ocean is less active and *vice-versa*. This see-saw in convection between the two ocean basins may be a manifestation of large scale air-sea interaction. The sub-tropical high over Australia also takes part in this oscillation. South Indian Ocean data from Voluntary Observing Fleet has to be examined to see whether Mascarene high is taking part in this oscillation.

(c) There is possibility of medium range forecasting of West Pacific cyclogenesis as it is related to convection over the north Indian Ocean through the 30-50 day oscillation.

(d) West Pacific cyclogenesis during the pre-monsoon months may be useful as a predictor for the long range forecasting of Indian summer monsoon rainfall. However, this has to be studied using data of many more years.

(e) Since the convective heat source generated in West Pacific Ocean during periods of cyclogenesis affects the tropospheric circulation features over both West Pacific and north Indian Oceans, some of the predictors using circulation features suggested for long range forecasting of monsoon rainfall of India may be related to the said cyclogenesis. It is necessary to conduct sensitivity tests using GCMs to know whether such circulation changes can be caused by a deep heat source in the tropical regions of West Pacific, north of the equator. The study by Keshavamurthy (1982) is one such study which deals with SST anomaly over central Pacific.

(f) Raman (1955) associates 'break monsoon' spells with typhoons in the West Pacific moving to the north of latitude 30° N. This northward motion can easily be explained. When West Pacific becomes convectively active, the intense atmospheric heating creates an anticyclone in the upper troposphere which steers the tropical cyclones of West Pacific northwards. It is well known that during break monsoon the Tibetan anticyclone shifts considerably southeastwards.

(g) From the proposed mechanism for the 30-50 day mode, it can be inferred that in the ocean basin having higher sea surface tamperature, ET will be active for the longer period in each 30-50 day cycle. Thus a warm SST anomaly in north Indian Ocean or cold SST anomaly in West Pacific Ocean is favourable for good (excess) monsoon rainfall over India. Joseph and Pillai (1986) find that a deficient monsoon (in rainfall) warms the tropical Indian Ocean and this warm SST anomaly changes the monthly mean atmospheric circulation over India to the type found in good monsoon years. Thus interannual variability of the Indian monsoon rainfall is closely related to its intraseasonal (30-50 day mode) variability. Such a possibility has been suggested by Gadgil (1988). It is important in this connection to note that long break monsoon spells are one of the characteristic features of deficient monsoon years.

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