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Onset of southwest monsoon- A study of the precursors in South Indian Ocean

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ABSTRACT
Satellite observed cloud data from the Indian Ocean region are now available for more than 50 years. An analysis of the cloud data for a period of 16 years (1972-1989 except 1978 and 1981), had shown that precursors to monsoon develop as different features in the activity of South Indian Ocean Convergence Zone (SIOCZ) (Eq.-20°S and 40-100°E). This had formed the basis for proposing SIOCZ model of long range forecast of rainfall over India, during the southwest monsoon period. Cloud data from 1990 onwards were used for preparing forecast on the real time basis and to further improve the model. The model has since produced reasonably good forecast of monsoon rainfall for India as a whole and also for individual meteorological subdivisions (numbering 36) for a period of 29 years (1990-2018), and in the districts of Tamilnadu for 14 years (2005-18), Himachal Pradesh for 11 years (2008-18), Andhra Pradesh and Telanagana for 4 years (2015-18) and Maharashtra and Goa for 3 years (2016-18). This has confirmed close relationship between the precursors as identified in cloud data, and the activity of southwest monsoon over India. In some of the years, the precursor did change during the season. Change in the rainfall scenario, resulting due to the change in the precursor, is included in the forecast update/updates. The relationship between precursors and onset of monsoon over Kerala has been further studied using satellite observed cloud data for a period of 50 years (1969-2018). It has been shown that (i) onset of monsoon over Kerala is related to the development of precursor, as a feature in the activity of SIOCZ, (ii) there is no one to one relationship between the date of onset and the performance of monsoon, and (iii) a close relationship between the precursors and the activity of monsoon during the season, has resulted in providing a reliable information on the performance of monsoon.

Key words: Southwest monsoon, Satellite observed cloud data, South Indian Ocean Convergence Zone, Rainfall.

INTRODUCTION

Southwest Monsoon (SWM) sets in over south Andaman Sea, Andaman and Nicobar Islands and parts of southeast Bay of Bengal by 20th May. It takes another 10 days for SWM to arrive over Kerala. The term onset generally refers to the first arrival of monsoon over Kerala and the term 'monsoon has advanced' is used to indicate its arrival over other regions of India. Utilizing daily mean rainfall from dense rain gauge networks in Kerala, for the period 1901-1980, Ananthakrishnan and Soman (1988) had shown that the mean onset date for south Kerala is 30th May and it is 1st June for north Kerala. Kerala extends from lat. 8° 15′ N to lat. 12° 50′ N. The dividing line between north and south Kerala is around Lat. 10° N.

Joseph et al. (1994) have given a critical review of the literature on the onset of monsoon over Kerala. Joseph et al. (2003) have also discussed the conditions leading to onset of monsoon over Kerala and the associated Monsoon Hadley Cell. The date of onset of monsoon over Kerala is determined by India Meteorological Department (IMD). Determining the date of onset is based on rainfall, wind field and Outgoing Longwave Radiation (OLR) data. If after 10th May, 60% of the 14 stations, viz., Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuza, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Kannur, Kudulu and Mangluru report rainfall of 2.5 mm or more for two consecutive days, the onset over Kerala is declared on the 2nd day, provided that (i) the depth of the westerlies are maintained up to 600 hPa level in the box, between equator & 10°N and long. 55-80°E and the zonal wind speed over the area bounded by lat. 5-10°N and long. 70-80°E are of the order 15-20 Kts at 925 hPa level. The source of wind data can be, analyzed wind/satellite derived wind from the Regional Specialized Meteorological Centre (RSMC) New Delhi, and (ii) INSAT derived OLR value which should be below 200 watts/square meter in the box bounded by lat. 5-10°N and long.70-75°E. Prior to the availability of winds/cloud motion vectors and OLR data, determining the date of onset was based on the rainfall data alone and the stations chosen for the purpose were, Colombo (Sri Lanka), Minicoy, Trivendrum (now Thiruvananthapuram), Alleppey, Cochin, Kozhikode and Mangalore (now Mangaluru) (Ananthakrishnan, et al., 1967). The normal date of

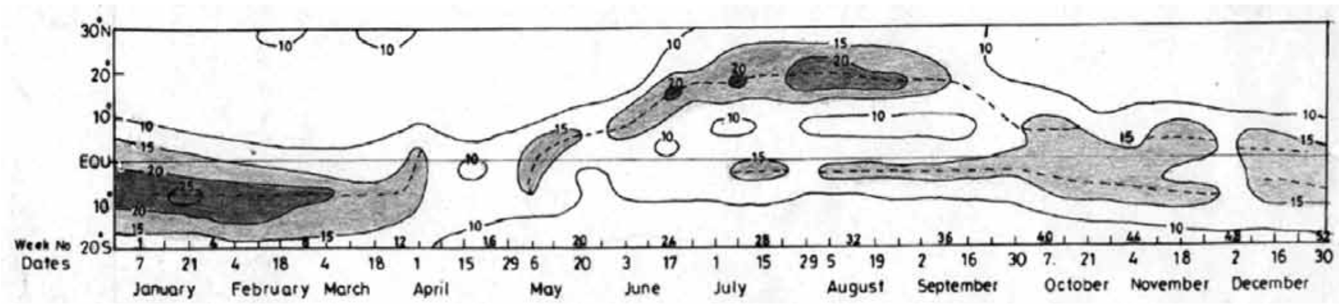

Figure 1. Long period zonal weekly mean cloudiness over the region bounded by Lat. 20ºS-30ºN and Long. 40-100ºE. The contours have been drawn for 10%, 15%, 20% and 25% area covered by cloudiness. Areas covered by 15% cloudiness and more have been shaded. [Period: (i) January-May 1972-2012. There were some missing data in 1972, 1978 and 1979, (ii) June-December 1983-2005]

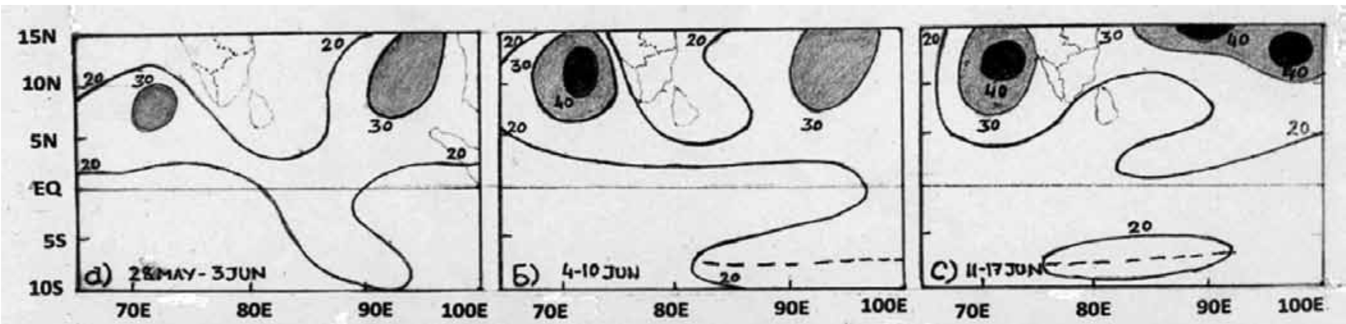

Figure 2. Long period weekly mean cloudiness during the weeks ending on 3rd, 10th and 17th June. Contours have been drawn at 20%, 30%, 40%, and 60%. Areas covered by 30% cloudiness and more have been shaded. [Period: Figure 2(a):1973-2012. Data for 1978 were missing. Figure 2(b) and 2(c): 1983-2005]

onset of monsoon over Kerala is 1st June and the Standard Deviation (S.D.) in the date of onset over Kerala is 8 days. In this study, we have used data on the dates of onset of monsoon over Kerala as determined by IMD.

Cross Equatorial Flow

Establishment of Cross Equatorial Flow (CEF) in north Indian Seas (Arabian Sea and the Bay of Bengal), is the single most important factor in onset and advance of monsoon. Both, development of deep layer westerlies and low values of OLR, are associated with the development of CEF in east Arabian Sea. Year to year variation in the date of onset is, therefore, related to variation in development of CEF. Existence of an east-west oriented Maximum Cloud Zone (MCZ) in satellite observed cloudiness in the near equatorial regions of oceans, is a visible manifestation of the existence of Inter-Tropical Convergence Zone (ITCZ). The term South Indian Ocean Convergence Zone (SIOCZ) refers to Indian Ocean (IO) part of ITCZ. SIOCZ generally develops between Long. 40-100ºE and between equator and 5ºS during monsoon months. In an extreme case, it could move southward up to 15ºS. Its location and intensity is closely related with the activity of SWM over India. Figure 1, prepared using long period cloud data from the region bounded by Lat. 20ºS-30ºN and Long. 40-100ºE, shows the location and northward propagation of MCZs developing in SIOCZ. An E-W oriented MCZ in the zone of SIOCZ could be seen in South Indian Ocean (SIO) during the period January-March only. There is a reduction in convection during April and, in general, northward movement of the MCZ begins in May. However, there are year- to-year variations in it. Figure 2 shows the development and movement of MCZ over the region bounded by Lat. 10ºS-15ºN and Long. 65-100ºE in the weekly mean cloud data. Two well known features associated with the onset of monsoon, i.e., development of convection and formation of an 'Onset vortex' at the leading edge of the monsoon current in east Arabian Sea, are also seen in cloud data. Development of an 'Onset vortex' is seen as a circular cloud mass in east Arabian Sea. One of the aims of the present study is to examine the relationship between the features developing in the activity of SIOCZ during pre-monsoon months and the date of onset of southwest monsoon over Kerala.

Long range forecasting

Long range forecasting of monsoon rainfall has remained an important aspect of weather forecasting in India because of the challenges in foreshadowing extreme seasons (excess/drought) and preparing forecast for individual subdivisions (numbering 36) and their clusters of districts/ districts. SIOCZ model (Gupta and Prasad, 1992, 1993; Onkari Prasad, 1993; Onkari Prasad et al., 2010b; Onkari Prasad and Singh, 2012; Onkari Prasad et. al., 2014) had been providing subdivision-wise long range forecast of SWM rainfall since 1990. District level Long Range Forecast (LRF) of seasonal rainfall are being provided for Tamilnadu for the past 14 years (2005-18) (Onkari Prasad, et al.,2010a), Himachal Pradesh for the past 11 years (2008-18), Andhra Pradesh and Telangana for the past 5 years (2014-18), Maharashtra and Goa for the past 3 years (2016-18) (Onkari Prasad, et al.,2016). This model has several advantages over other models: (i) the model is simple and requires only one data, i.e., satellite observed cloud/OLR from IO region, (ii) it is robust as it has produced reasonably good forecast for the past 29 years, (iii) this model alone could foreshadow the droughts in 2002, 2004 and 2009 and severe rainfall deficiency during June-July of 1992 and 2012, (iv) forecasts from the model were reasonably good for India as a whole, as well as in meteorological subdivisions and the districts of the six states as mentioned above. Recognition of the precursors, in the activity of SIOCZ, is the main feature of the model. Further, the identification of the precursors in cloud field had been reasonably good in each year during the past 50 year period (1969-2018).

DATA AND ANALYTICAL METHOD

Date of onset of SWM for a period of 50 years (1969-2018) (Table 1) and the estimates of satellite observed cloud data for the same period, are used in the present study. Visible cloud imagery from NOAA series of polar orbiting satellites for the period 1972-1983 and INSAT/METEOSAT- Indian Ocean Data Collection (METEOSAT- IODC) satellites for the remaining period had been used to obtain daily estimate of clouds (0%, 10%, 20%,.., 80%, 100%) in each 5° lat. x 5° long. boxes over the region bounded by Lat. 20°S-30°N and Long. 40-100°E. Using daily data, Weekly Mean Cloudiness (WMC) in each box has been worked out. Zonal Weekly Mean Cloudiness (ZWMC) has been prepared for each 5° lat. belt between 20°S and 30°N over the region bounded by Long. 40-100°E. WMC and ZWMC data for the period January-May 1973-2012 and June-December 1983-2005 have been used to obtain their long period mean. It may be mentioned here that digital cloud imagery data are not available regularly from any satellite, polar orbiting or geostationary. The cloud data for the period 1972-89 had been used for developing SIOCZ model for LRF of monsoon rainfall (Gupta and Onkari Prasad, 1992, 1993; Onkari Prasad,1993). Data for the period 1990-2018 have been used for issuing real time forecast and further improvement in the model (Onkari Prasad, et al., 2010b, Onkari Prasad and Singh, 2012, Onkari Prasad, et al., 2014). The information on the precursors, developing in the activity of SIOCZ, as identified in cloud data, are now available for a period of 47 years (1972-2018). Spectral analysis of daily digital cloud data from NOAA series of polar orbiting satellites for the years 1966-73 by Yasunari (1980) had shown a dominant mode of 30 to 40 days, a feature related to development of a normal SWM, in all the other years, except 1972 when the dominant periodicity was 60 days. Yasunari (1980) also composed the time-latitude cross sections of band-pass filtered cloudiness over the longitudinal sector of 70-90°E for the years 1966-73. A northward propagation of cloudiness was seen in all the years. It has been indirectly inferred that a precursor for development of a normal monsoon was present in the cloud data for the pre-monsoon months in the years 1969-71. The precursors identified for development of Excess (E)/Active(A)/Normal(N)/Weak(W)/Deficient(D) monsoon (Table 1) form another set of data used in the study.

It follows from Table 1 that onset had taken place either around the normal date or within 1 S.D. in the date of onset in 43 (86%) years. Onset was early in 5(10%) years and delayed in 2(4%) years only. Development and northward movement of MCZs and precursors identified in the activity of SIOCZ during E/A/N/W/D monsoon during the period of study are discussed below.

Early onset of SWM

Early onset of SWM in 1972

1972 was a severe drought year and ISMR was 26% below normal. The % departure of weekly rainfall over Kerala during the weeks ending on 3rd, 10th and 17th May 1972 was -11%, 100% and 559% respectively. Temporary onset of monsoon had been indicated over Kerala on 13th May. The % departure of rainfall over Kerala during the weeks ending on 14th, 21st and 28th June was -96%, -64% and 2% respectively. A regular onset had been declared on 18th June. The increase in rainfall was more marked during the first spell, as compared to the second. We have, therefore, included 1972 in the years of early onset.

Figure 3 shows time-latitude cross section of ZWMC during the period 1st April- 30th June 1972. The main feature was the appearance of a 7 week period between the development of two active spells of SIOCZ- a feature recognized as a precursor to development of a severe all India drought in the new approach to long range forecasting of monsoon rainfall in India based on SIOCZ model (Gupta and Onkari Prasad, 1992; Onkari Prasad and Singh, 2012). A MCZ had developed during the week beginning on 14th April in the 5° lat. belt of 10-15° S. It had moved northward up to 20°N by the week ending on 19th May. The next MCZ in the zone of SIOCZ developed during the week ending on 16th June. It moved up to 15°N during the week ending on

Table 1. Year, date of onset of SWM, precursor to development of an Excess(E)/Active(A) /Normal(N)/Weak(W)/Deficient(D) monsoon and % departure of Indian Summer Monsoon Rainfall (ISMR) from its long period average (100%) during the period 1969-2018

Year	Date of onset	Pre-cursor	% departure of ISMR	Year	Date of onset	Pre-cursor	% departure of ISMR	Year	Date of onset	Pre-cursor	% departure of ISMR
1969	16May	N	1	1986	4June	D	-13	2003	8June	A	5
1970	24May	N	12	1987	2June	D	-18	2004	18May	D	-14
1971	31May	N	4	1988	26May	E	18	2005	5June	D	-1
1972	13May	D	-26	1989	3June	N	1	2006	26May	N	0
1973	19May	N	6	1990	19May	A	6	2007	28May	N	5
1974	25May	D	-15	1991	2June	W	-9	2008	31May	N	-2
1975	31May	E	12	1992	5June	D	-8	2009	23May	D	-23
1976	30May	N	0	1993	28May	N	0	2010	31May	N	2
1977	30May	N	4	1994	28May	A	10	2011	29May	N	-5
1978	28May	A	7	1995	8June	N	0	2012	5June	D	-8
1979	11June	D	-21	1996	3June	N	3	2013	1June	A	6
1980	1June	N	0	1997	9June	N	2	2014	6June	D	-12
1981	31May	N	4	1998	2June	N	6	2015	5June	D	-15
1982	28May	D	-14	1999	25May	A	-4	2016	8June	D	-3
1983	12June	A	13	2000	1June	W	-8	2017	30May	W	-5
1984	31May	W	-4	2001	23May	W	-9	2018	28May	N@	-9
1985	28May	W	-8	2002	29May	D	-19				

Excess (E) : ISMR >10%, Active (A): 10 - 5%, Normal (N): 4 - -4%, Weak(W): -5 - -10%, Deficient (D): < -10%. @ Forecast was downgraded to 'W' monsoon on 11th July 2018. In 1972, an early onset on 13th May had been termed as temporary onset. Regular onset had been declared on 18th June.

23rd June. The period between the developments of these two MCZs was 7 weeks. As mentioned above, spectral analysis of daily digital cloud data of the years 1966-73 (Yasunari, 1980), had shown a dominant mode of about 60 days in 1972. Yasunari (1980) had also composed time-latitude cross sections of band-pass filtered cloudiness over the longitudinal sector of 70-90^{o}E for the years 1966-73. A northward propagation of cloudiness, similar to other years, i.e., 1966-71 and 1973, was also seen in 1972, but the dominant periodicity was at about 60 days.

Figure 4 shows WMC during the weeks ending on 12th, 19th and 26th May 1972, associated with the development and movement of the MCZ in May. Similarly, Figure 5 shows WMC during the weeks ending on 16th, 23rd and 30th June 1972, associated with the development and movement of the MCZ in June. But for its early arrival over Kerala, development, northward movement and the northern limit to which the MCZ had reached during May was very similar to that of the MCZ which had developed in June. The difference was only in the reduction of cloudiness in the Arabian Sea and quick movement of cloudiness northward in the Bay of Bengal during the week ending on 26th May. An important observation has been that a period of 7-8 weeks between the developments of the two MCZs was a precursor to development of a severe drought in 1972.

Early onset of SWM in 1918

The earliest onset of SWM on record, was in the year 1918, when SWM had set in over Kerala on 11th May (Ananthakrishnan, et al., 1967). 1918 was also a severe drought year, like 1972. The rainfall for the country as a whole was 25% below normal and comparable to that in 1972 (26% below normal). Thus, there is a similarity between onset as well as the performance of monsoon in 1972 and 1918. As cloud data were not available for 1918, weekly rainfall of 3 southern most subdivisions of India, namely, Bay Islands, Madras (Tamilnadu), and Malabar (Kerala) during pre-monsoon months of 1918 (Figure 6), had been examined by Gupta and Onkari Prasad (1992), in a manner similar to that used by Joseph and Pillai (1988), for the occurrence of a period of 7-8 week in rainfall during the pre-monsoon months of 1918. A significant increase in the rainfall is seen during the week ending on 21st March over Malabar and in all the 3 subdivisions in the subsequent week. The second significant increase in the weekly rainfall over Malabar was recorded during the week ending on 9th May. The period between the two spells of increased rainfall comes out to be 7 weeks. The onset of monsoon over Malabar had been declared on 11th May. Similarly, after the onset, the subsequent significant increase in weekly rainfall occurred during the week ending on 4th July, i.e., after a

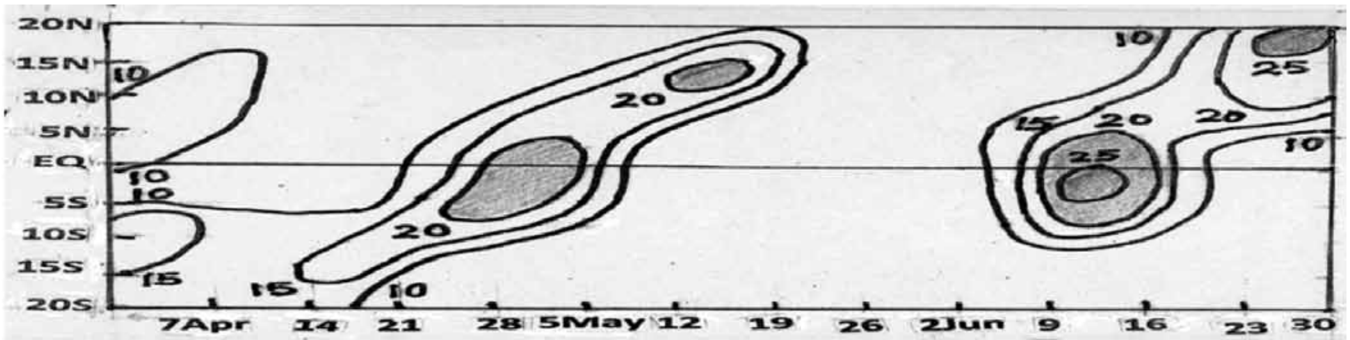

Figure 3. Time-latitude cross section of zonal weekly mean cloudiness from the week ending on 7th April - the week ending on 30th June 1972 over the region bounded by 20ºS-20ºN and 40º-100ºE. Areas covered by the contours of 20% or more cloudiness have been shaded

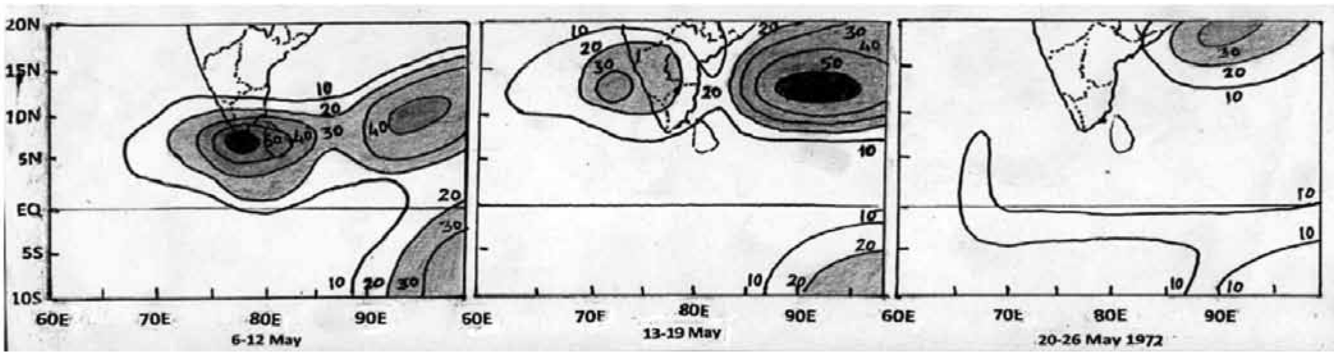

Figure 4. Weekly mean cloudiness during the weeks ending on 12th, 19th and 26th May 1972

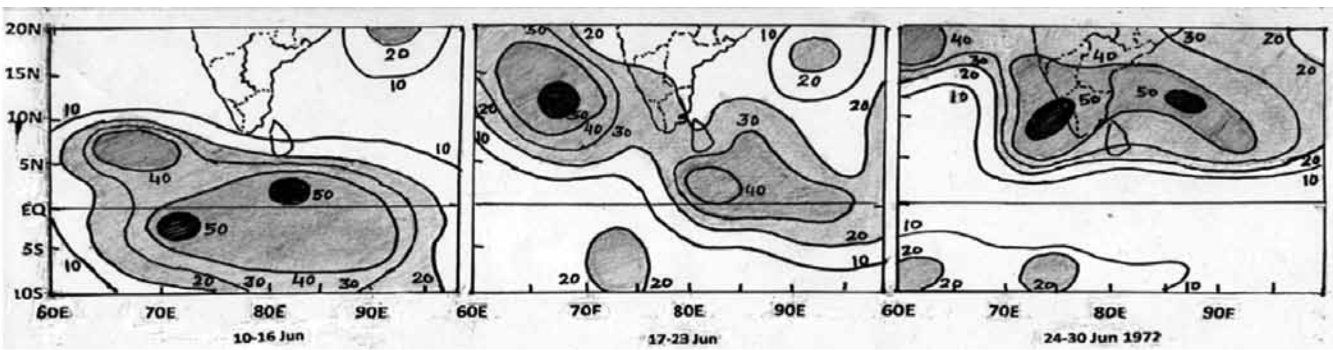

Figure 5. Same as Figure 4 but for the weeks ending on 16th, 23rd and 30th June 1972

period of 8 weeks. The fourth significant increase in rainfall over Malabar was recorded during the week ending on 22nd August. Here again the period between the rainfall peaks comes out to be 7 weeks. This confirms the occurrence of a period of 7-8 week in rainfall over Malabar during 1918 SWM. Appearance of a period of 7-8 weeks in the development of MCZs in 1972/rainfall peaks in 1918 was a precursor to development of a drought with deficiency of rainfall, of the order of 25% below normal.

Early onset of SWM in 1973

In 1973, the onset of SWM had taken place on 19th May, i.e., 12 days before the normal date. Rainfall, for India as a whole, was 6% above normal. The ZWMC for the period 4th March -27th May 1973, are shown in Figure 7 and WMC for the weeks ending on 12th, 19th and 26th May in Figure 8. Development of MCZs with a tendency to move northward was the characteristic feature in the cloud field during the period March-May 1973. The period between the MCZs, which had developed during April-May, was 4 weeks. Cloudiness extended from east Arabian Sea to the Bay of Bengal across Kerala and Tamilnadu during the week ending on 12th May. After onset, cloudiness did not move northward during the subsequent week. A period of 4 weeks in the development of MCZs in the zone of SIOCZ and their northward movement was a precursor to development of an active monsoon in 1973.

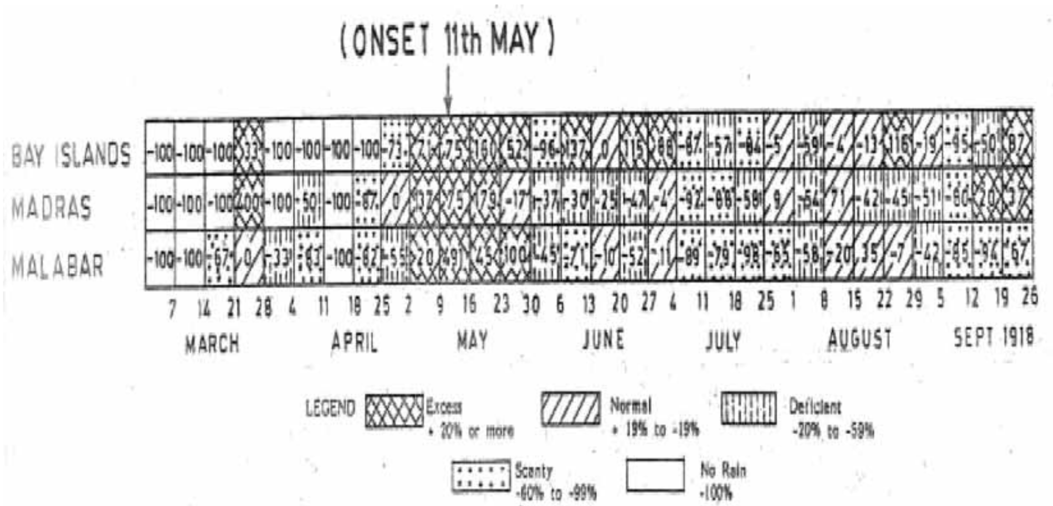

Figure 6. Percentage departure of weekly rainfall from normal.

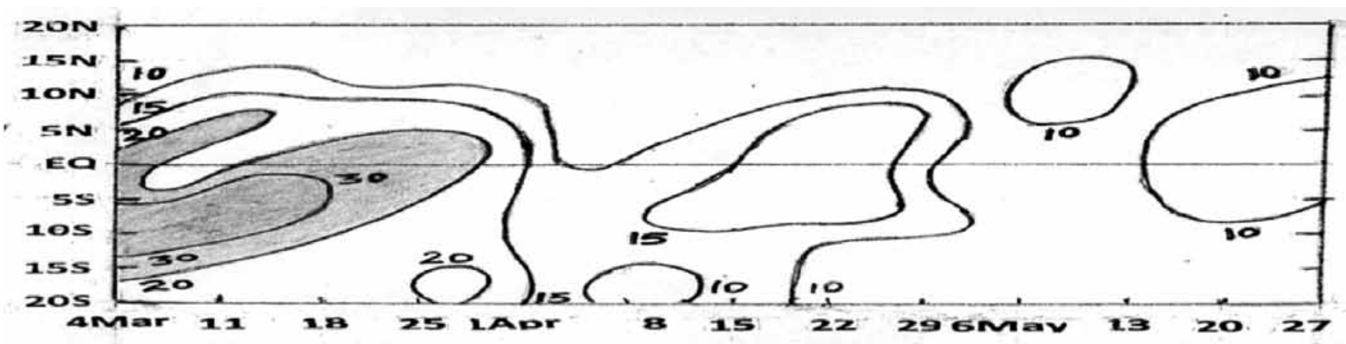

Figure 7. Same as Figure 3 but from the weeks ending 11th March- week ending on 27th May 1973.

Early onset of SWM in 1990

SWM had set in over Kerala on 19th May, i.e., 12 days in advance, in 1990. The ZWMC for the period from the week beginning on 7th April to -week beginning 30th June 1990 are shown in Figure 9 and WMC during the weeks ending on 12th , 19th and 26th May in Figure 10. Four MCZs had developed during the weeks ending on 7th April, 12th May, 9th June and 30th June. The average period between them comes out to be 3 weeks. The second MCZ, which developed to the south of equator during the week ending on 12th May, was quite active, convection associated with it weakened to the south of equator, it developed to the north of equator and had reached up to Kerala coast during the subsequent week (Figure 10). Onset had been declared on 19th May. Appearance of an average period of 3 weeks in the development of MCZs and progressive northward movement of the second MCZ was a precursor to development of an active monsoon during 1990.

Early onset of SWM in 2004

Southwest monsoon had set in over Kerala on 18th May 2004, i.e., 13 days in advance. ZWMC for the period from the week ending on 7th April- the week ending on 30th June, are shown in Figure 11 and WMC for the weeks ending on 12th ,19th and 26th May in Figure 12. Out of the four MCZs which had developed in the zone of SIOCZ during April-June, only two of them which had developed during the week ending on 7th April and 16th June were prominent. The other two were short lived and did not show movement. The MCZ which developed during the week ending on 7th April weakened slightly during the next week. It continued to move northward. However, the northward movement was sluggish. The MCZ could reach 5^{o} lat. belt of 10-15^{o} N by the week ending on 12th May. Onset of 2004 monsoon had been declared on 18th May. Development of a period of about 8 weeks between the two prominent MCZs, Sluggish northward movement of one of the prominent MCZ, development of another 2 short lived MCZs, were the features identified in the activity of SIOCZ. Collectively, a precursor to development of a weak monsoon had been inferred in 2004.

Normal onset of SWM

Out of 43 years when onset was either on the normal date or within 1 S.D. in the dates of onset, the precursor

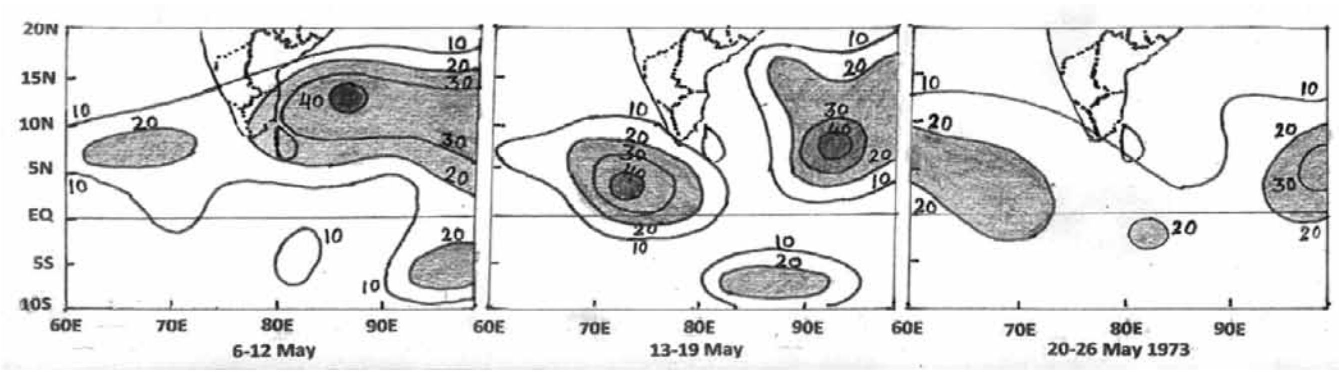

Figure 8. Same as Figure 4 but for the weeks ending on 12th, 19th and 26th May 1973.

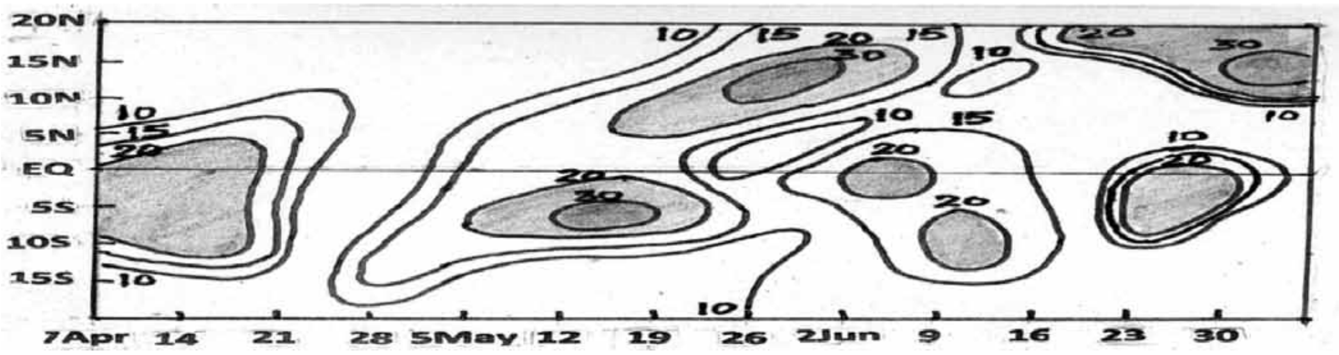

Figure 9. Same as Figure 3 but from the week beginning from 7th April-week beginning on 30th June 1990.

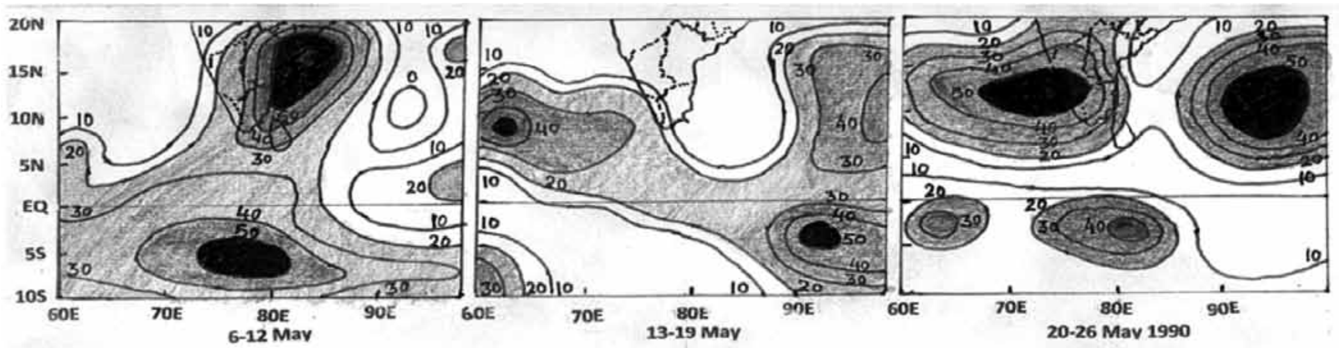

Figure 10. Same as Figure 4 but for the weeks ending on 12th, 19th and 26th May 1990.

for development of a normal/active monsoon was present in 25(50%) years. Thus in the majority of the years of normal onset, India had received normal rainfall. During 2 years, i.e., 1975 and 1988, the precursors were for excess monsoon and the realized rainfall, for country as a whole, was also in excess category. During 6 years (1984, 1985, 1991, 2000, 2001 and 2017), the precursors were for weak monsoon. The realized rainfall was in below normal category in 5 years and it was in normal category, but on the lower side of normal, in 1 year, i.e., 1984. In the remaining 10 years of normal onset (1974, 1982, 1986, 1992, 2005, 2009, 2012, 2014, 2015 and 2016), the precursors were for deficient rainfall. The realized rainfall was in deficient category in 7 years, in below normal category in 2 years (1992 and 2012) and in normal category in one year (2005). Intra-seasonal changes were responsible for improvement in rainfall during the years 1992, 2005, 2012 and 2016. Intra-seasonal changes are not limited only to some of the years and these changes are not exclusively dependent on the activity of SIOCZ. This aspect becomes clear from the discussions, presented below, on intra-seasonal changes during the years 1992,2005,2012,2016 and 2018.In the normal onset year of 2018, the precursor was for a normal monsoon. However, a feature in the activity of SIOCZ, relating to development of a weak monsoon had just appeared in May. Intra-seasonal changes and their impact on rainfall in these 5 years have earlier been studied by Onkari Prasad, et al. (2014, 2018) and

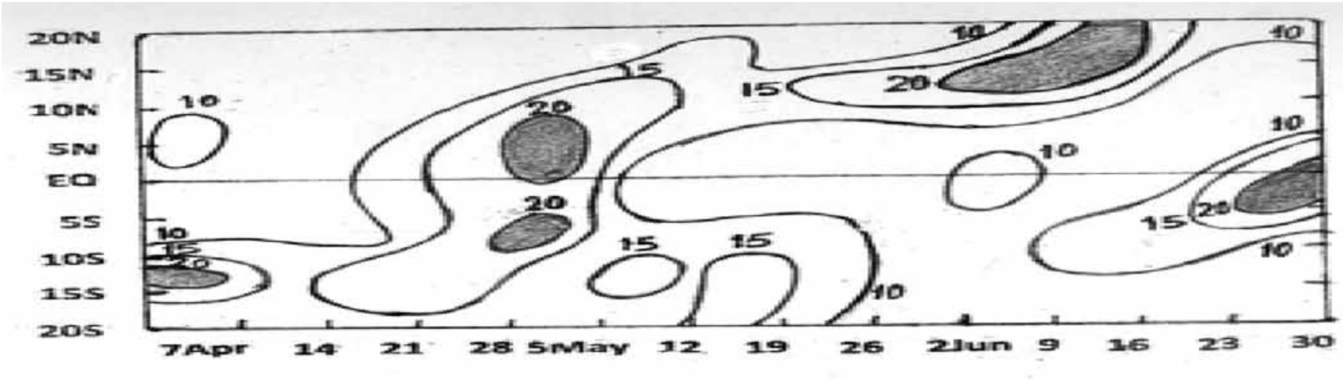

Figure 11. Same as Figure 3 but from the week ending on 7th April- the week ending on 30th June 2004.

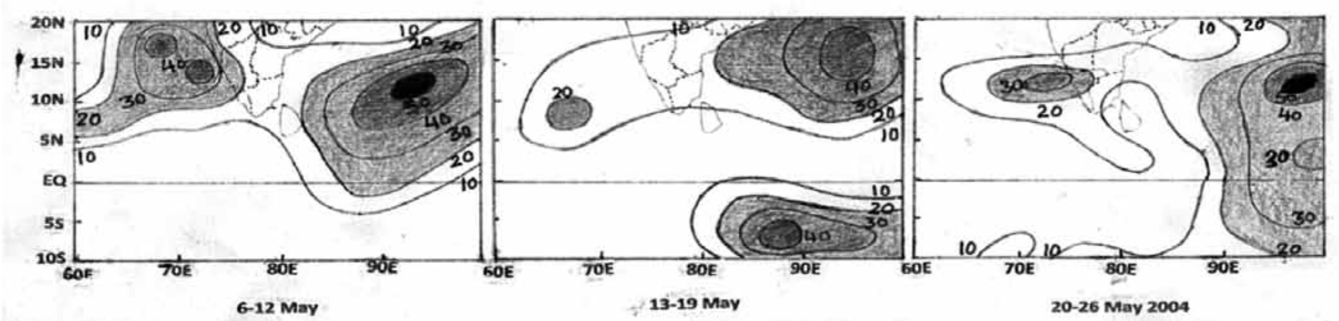

Figure 12. Same as Figure 4 but for the weeks ending on 12th, 19th & 26th May 2004

the results are briefly summarized below. Due to lack of space, the figures showing ZWMC during April-June and northward propagation of the MCZs during three weeks, i.e., week before the onset, during the week of onset and the week subsequent to the week of onset, could not be reproduced for normal onset years. Development of a MCZ in the zone of SIOCZ at an interval of 4-6 weeks and its northward propagation up to 10^o N lat. or further north in the east Arabian Sea around the normal date of onset, or within one S.D. in the date of onset, was common to most of the years of normal onset.

The precursor identified for 1992 SWM was that for a severe drought with 16% below normal rainfall for country as a whole and as per the improved version of SIOCZ model (Onkari Prasad and Singh,2012; Onkari Prasad, et al., 2014), the forecast rainfall was 11% below normal, i.e., in deficient category. Severe drought conditions prevailed over India during the first half of the season: The weekly cumulative rainfall, for India as a whole, was below normal by 20% till the end of July. Thus, the rainfall during the first half of the season was well captured by SIOCZ model. Monsoon trough strengthened during the second half of the season and rainfall situation improved. Rainfall was 8% below normal at the end of the season. The intra-seasonal changes occurred in association with the ongoing changes in the Equatorial Indo-Pacific region: El- Nino of 1991-92, which had been at its peak during December 1991-February 1992, started weakening and ENSO-neutral conditions returned from July and continued till the end of the season. The intra-seasonal changes in the activity of SIOCZ and improvement in rainfall scenario over India began in August and continued in September also.

The forecast for 2005 SWM was 14% below normal rainfall and with the improved version of the model, it was 9% below normal. The realized rainfall was 1 % below normal. The precursor identified for 2005 SWM was that for a moderate drought/weak monsoon (Onkari Prasad, et al., 2014). The precursor, for a moderate drought/ weak monsoon, continued throughout the season. The cumulative rainfall for India as a whole was 8% below normal up to 7th September. However, the rainfall which occurred during the next 2 weeks, in association with the development and movement of the Bay of Bengal cyclonic storm of 17-21 September 2005, was able to reduce the deficiency from 8% to 1%. The cyclone initially moved across central India and then re-curved to north giving heavy rainfall in a number of subdivisions, where rainfall was deficient. The strengthening of monsoon circulation was related to the ongoing changes over the Equatorial Indo-Pacific region: demise of EL-Nino of 2004 and setting in of ENSO-neutral conditions from July 2005 onwards.

The precursor identified for 2012 SWM was that for a severe drought with 20% below normal rainfall (Onkari Prasad, et al., 2014). 2012 SWM displayed features of a severe drought during June and July. Rainfall was 28% below normal in June and 27 subdivisions, out of 36, had received deficient/scanty rainfall. No low pressure area formed in June and such a situation had not occurred during the past 31 year period of 1981-2011 (IMD, 2012). July rainfall was 13% below normal. Monsoon circulation strengthened during August and this situation continued up to the middle of September. A part of the deficiency was made up and the realized rainfall was 8% below normal by the end of the season. La Nina of 2011 had continued up to the three monthly period of February-March-April of 2012. SST anomalies became zero during the three months period of June-July-August and 0.3^{o}C during July-August-September 2012. So, the improvement in rainfall could not be attributed to the ongoing changes in Equatorial Indo-Pacific region. The improvement resulted due to the changes in the activity of SIOCZ: SIOCZ remained generally active during the second half of 2012 monsoon, but in the latitude belt of 15-20^{o}S, i.e., in its southern most location during the season. This coincided with the strengthening of monsoon trough. As per the inverse relationship between monsoon trough and SIOCZ, strengthening of monsoon trough was not expected during the second half of 2012 SWM also. The inverse relationship between monsoon trough and SIOCZ was nearly ineffective in the reduction of rainfall over India during the second half of the season. Monsoon trough remained active and quasi-stationary in its normal location for a period of one and a half month, i.e., during August-first half of September 2012. SIOCZ is most effective in weakening the monsoon trough and, thereby, in reduction of rainfall over India when it is active in its normal location during the season, i.e., between equator-5^{o}S lat. Though active, but being located between 15-20^{o} *S* lat., SIOCZ could not weaken the monsoon trough. The improvement in rainfall during the second half of 2012 SWM had, therefore, resulted due to the extreme southern most location (15-20^{o} S) of an active SIOCZ.

The precursor identified for 2016 SWM was that for a deficient monsoon with 14% below normal rainfall for India as a whole (Onkari Prasad, et al., 2018a). Except for the month of July when rainfall, for country as a whole, was above normal by 7%, rainfall was below normal by 11%, 9% and 3% in June, August and September respectively. Severe drought like conditions prevailed over north India and south peninsula in August and over NW India and south peninsula in September. For the season as a whole, rainfall was 6% above normal over central India, but it was below normal in NW India, NE India and south peninsula by 5%, 8% and 11% respectively. Seasonal rainfall for country as a whole was 3% below normal. Intra-seasonal changes were responsible for improvement in rainfall: A mid season transition from ENSO neutral-to-La Nina had taken place during 2016 monsoon. La Nina conditions prevailing during August-September had been found to be generally associated with an active monsoon conditions over India. But this did not happen in 2016. Changes in the activity of SIOCZ were more closely related to the distribution of rainfall over India during the second half of 2016 SWM than the mid-season transition from El Nino-ENSO Neutral-La Nina conditions in Equatorial East Pacific. Beginning from 2013, forecast updates are being issued to take into account the changes in monsoon circulation system and thereby in rainfall, resulting due to intra-seasonal change as seen in the appearance of a new feature in the activity of SIOCZ. The improvement in rainfall had been captured in the update issued on 1 Aug 2016, wherein, the forecast had been upgraded to a normal monsoon (100% of long period average) (Onkari Prasad, et al., 2018a).

Based on OLR and cloud data up to March 2018, the main feature identified for 2018 SWM was that for development of a normal monsoon and accordingly, the qualitative long range forecast for seasonal rainfall for India as a whole, issued on 11th April 2018 (Onkari Prasad, et al., 2018b) was for a normal monsoon. The quantitative forecast issued on 5th June (Onkari Prasad, et al., 2018b) was also that for a normal monsoon with 2% above normal ISMR. But, a precursor, relating to development of a weak monsoon, appeared in May. A mention of this had been made in the quantitative forecast issued on 5th June. The precursor relating to weak monsoon repeated during June and during the first week of July also. Accordingly, the forecast was downgraded to a weak monsoon with 7% below normal rainfall for country as a whole, in the update issued on 11th July (Onkari Prasad, et al., 2018b). The realized rainfall for country as a whole for 2018 SWM was 9% below normal. It follows from the above discussions that the identification of the precursors was satisfactory in 1992, 2005, 2012, 2016 and 2018. The intra-seasonal changes in monsoon circulation system and the corresponding changes in rainfall scenario in 2016 and 2018 had been captured in the update.

Delayed onset of SWM

Delayed onset of SWM in 1979

1979 was a severe drought year with 21% below normal rainfall for country as a whole. Onset over Kerala had been delayed by 11 days. The ZWMC for the period April-June 1979 are shown in Figure 13. Onset occurred during the northward propagation of the MCZ which had developed over the equator during the week ending on 3rd June. Initially, the MCZ remained confined to the areas between 5^{o} lat. on either side of the equator. Northward propagation began only during the week ending on 10th June. Onset took place on 11th June. The MCZ which had developed during the last week of May remained practically stationary and close to equator. This caused delay in onset of monsoon in

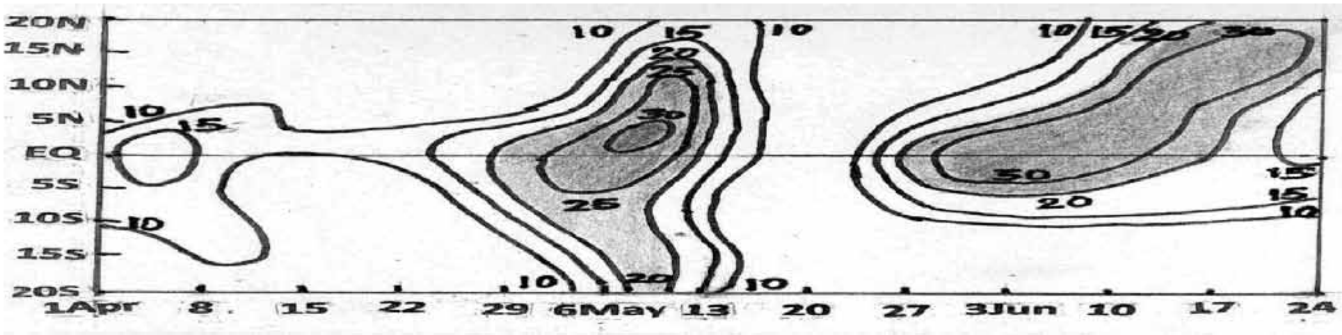

Figure 13. Same as Figure 3 but from the week ending 8th April- week ending 24th June 1979

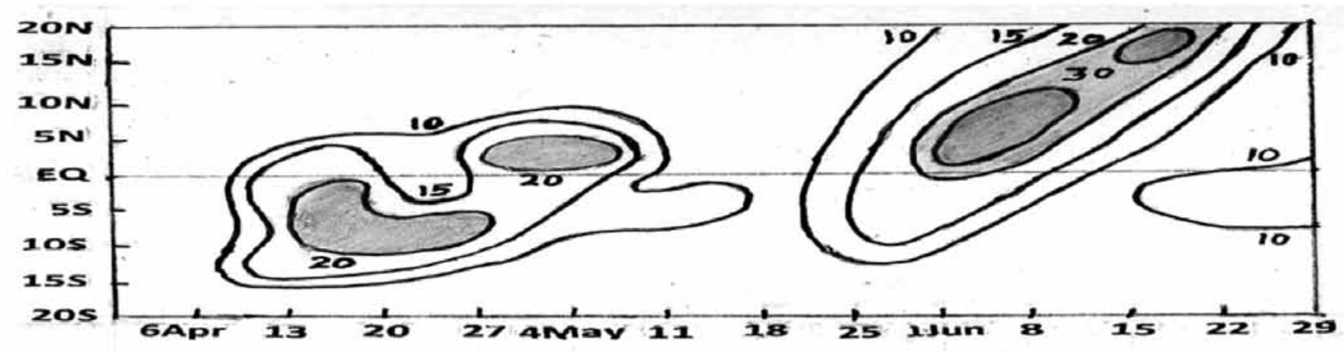

Figure 14. Same as Figure 3 but from the week ending on 6th April- the week ending on 29th June 1983

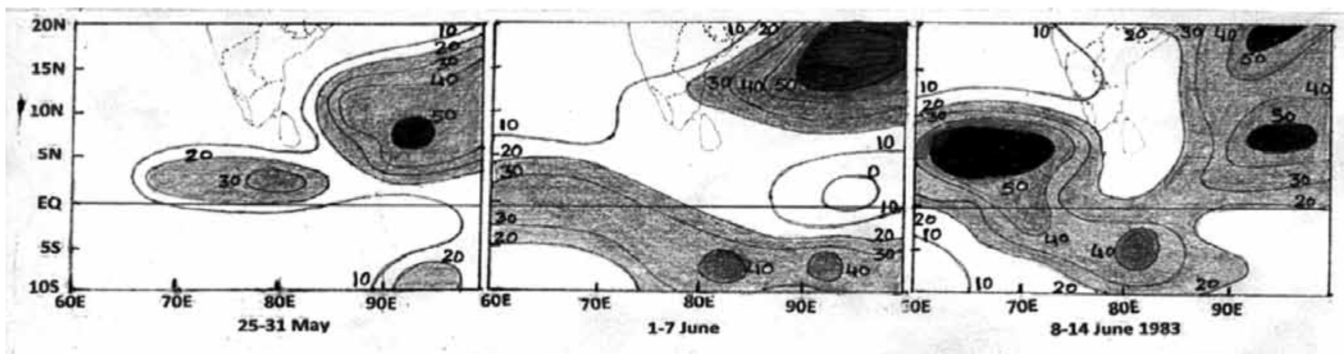

Figure 15. Same as Figure 4 but for the weeks ending on 31st May, 7th and 14th June 1983.

1979. The WMC data are not available for the year 1979 and hence the figure showing week by week propagation of the MCZ could not be included here.

The MCZs which had developed in the beginning and at the end of April, had a tendency to move towards north as well as towards south of equator. This was more clearly seen in the MCZ which had started developing over the equator during the last week of April. Movement of MCZs on either side of the equator was a precursor for likely development of a weak monsoon/drought during 1979.

Delayed onset of SWM in 1983

SWM had set in over Kerala on 13th June in 1983. 1983 was an excess monsoon year with 13% above normal rainfall for India as a whole. ZWMC for the period 6th April- 29th June 1983 are shown in Figure 14. The WMC during the weeks ending on 31st May, 7th June and 14th June 1983 are shown in Figure 15. The MCZ had reached up to 15ºN in the Bay of Bengal and up to 5º N in the east Arabian Sea by the week ending on 31st May. The MCZ to the north of equator was expected to move northward and reach Kerala coast during the next few days. However, during the subsequent week, i.e. during the week ending on 7th June, there was considerable reduction in the cloudiness in east Arabian Sea. The MCZ was now seen between 5ºN-5ºS over the areas in the sector 60-70º E, giving an impression as if the MCZ had shifted southwards. In fact, the northward moving MCZ had weakened and a fresh MCZ had developed close to equator but south of it. This

MCZ extended further eastward and it was seen between 5-15^{o}S east of 80^{o}E, where it was more marked. The MCZ was not confined to SIO alone, but it extended over south West Pacific also. This situation changed in the subsequent week. The MCZ in the sector 55-80^{o}E moved northward and reached up to 10^{o}N in east Arabia Sea. Onset of SWM was declared on 13th June. It is interesting to note that the development of an active spell of SIOCZ for one week did not repeat till the end of 1983 monsoon season. Development of SIOCZ during 1-7 June 1983 had caused considerable weakening of the convergence zone to the north of equator and hence a delay in the onset of monsoon over Kerala. The MCZ which developed in the zone of SIOCZ during the week ending on 13th April (Figure 14) remained active for the next 4 weeks and moved northward up to 5^{o} N lat.. This feature in the activity of SIOCZ was an indication of development of CEF in Arabian Sea and its sustenance for 4 weeks in continuation. Establishment of CEF in Arabian Sea in the beginning of Apr and its sustenance for 4 weeks in continuation was a precursor to development of an active-to-excess SWM during 1983.

CONCLUSIONS

There is a remarkable consistency in the date of onset of southwest monsoon over Kerala. During the period of 50 years (1969-2018), onset had taken place either around or within 1 S.D. in the dates of onset, in 86% years. Onset was early in 10% years and it was delayed in 4% years only. Development of a MCZ in the zone of SIOCZ during pre-monsoon months with a period of 4-6 weeks and its progressive northward movement up to about 10^{o} N or further north in the east the Arabian Sea is common to most of the years of normal onset.

Development of a MCZ at the end of April/beginning of May and its uninterrupted northward movement results in early onset. Development of a MCZ over the equator during the last week of May and its slow movement northward results in delay in onset, as was the case in 1979. Delay in onset may also result due to development of an active spell of SIOCZ during the first week of June as was the case in 1983.

Large intra-seasonal changes take place in southwest monsoon in some of the years, due to either development of new features in the activity of SIOCZ or changes in sea surface temperature over equatorial Indo-Pacific region. Monitoring of development of new features helps in issuing forecast update. Experience of issuing update for the past few years has shown that the updates were able to capture the changes in rainfall scenario over India.

Development of a MCZ in the zone of SIOCZ is linked to the development of a slow northeastward propagating mode, which originates in west IO and travels eastward. Inter-annual and intra-seasonal changes in this mode are linked to SST distribution over SIO. Further studies, using long period weekly mean cloud/OLR and weekly mean SST anomaly from SIO are required for understanding the mechanism of development of MCZs and the period between them.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

REFERENCES

Ananthakrishnan, R., Acharya, U.R. and Ramanathan, A.R., 1967. IMD, FMU Report No.1, November 1967, 'On the criteria for declaring the onset of southwest monsoon over Kerala', p.19.

Ananthakrishnan, R. and Somon, M.K., 1988. The onset of southwest monsoon over Kerala: 1901-1980, J. Climatology, 8, 283-296.

Gupta, G.R. and Onkari Prasad, 1992. Role of southern hemispheric equatorial trough in long range forecasting, Jalvigyan Sameeksha, VII, 83-97.

Gupta, G.R. and Onkari Prasaed, 1993. Southern hemispheric equatorial Trough model of long range forecast of monthly rainfall during southwest monsoon, J. Indian Association of Hydrologists, Hydrology J., 16, 49-76.

IMD, 2012, End of season report on 2012 southwest monsoon.

Joseph, P.V. and Pillai, P.V., 1988. 40 day mode of equatorial trough for long range forecasting of Indian summer monsoon onset, Curr. Sci., 57, 951-954.

Joseph, P.V., Eishcheid, J.K. and Pyle, R.J., 1994. Inter annual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El-Nino and seas surface temperature anomalies, J. Climate, 7, 81-105.

Joseph, P.V., Sooraj, K.P. and Rajan, C.K., 2003, Conditions leading to monsoon onset over Kerala and associated Hadley Cell, Mausam, 54(1), 155-164.

Onkari Prasad, 1993. Performance of Southern Hemispheric Equatorial Trough model of sub-division-wise long range forecast of rainfall during southwest and northeast monsoons, Proceedings of TROPMET Symposium-1993, held at New Delhi, 17-19 March 1993.

Onkari Prasad, Singh, O.P. and Subramanian, S.K., 2010a. Seasonal forecast of southwest monsoon rainfall- District level, J. Ind. Geophys. Un., 14, 93-113.

Onkari Prasad, Singh, O.P. and S. Prasad, 2010b, South Indian Ocean Convergence Zone model: A new approach to seasonal forecasting of monsoon rainfall in India Part I:South Indian Ocean Convergence Zone and its role in the development of Indian summer monsoon, J. Ind. Geophys. Un., 14(4), 233-248.

Onkari Prasad and Singh, O.P., 2012. South Indian Ocean Convergence Zone model: A new approach to seasonal forecasting of monsoon rainfall in India Part II: Forecast for India as a whole, J. Ind. Geophys. Un., 16(1), 1-10.

Onkari Prasad, Singh, O.P. and K. Prasad, 2014. South Indian Ocean Convergence Zone model: A new approach to seasonal forecasting of monsoon rainfall in India Part VI: Merits of the model and limitations in seasonal forecasting of rainfall in India, J. Ind. Geophys. Un.,18(3), 363-386.

Onkari Prasad, Singh, O.P. and K. Prasad, 2016. Long range forecast of rainfall during southwest monsoon in the states of Maharashtra and Goa, J. Ind. Geophys. Un., 20(6), 586-595.

Onkari Prasad, Singh, O.P. and K. Prasad, 2018a, 2016 southwest monsoon and its long range forecast, J. Ind. Geophys. Un., 22(1), 90-100.

Onkari Prasad, Singh, O.P. and Prasad, K., 2018b. Long range forecast of rainfall during 2018 southwest monsoon based on South Indian Ocean Convergence Zone model issued on 11th April and 5th June and update issued on 11th July 2018 submitted to IMD and user agencies of Govt. of India.

Yasunari, T., 1980. A quasi-stationary appearance of 30 to 40 day period in the cloudiness fluctuations during the summer monsoon over India, J. Met. Soc. Japan, Ser. II, 58, 225-229.

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