J. Ind. Geophys. Union (July 2013)
Vol.17, No.3, pp. 289-305

South Indian Convergence Zone Model: A new approach to seasonal forecasting of summer monsoon rainfall in India Part IV: Intra-seasonal changes and long range forecast of rainfall during 2010 southwest monsoon season

[1]Onkari Prasad and [2]O.P.Singh
[1]43, Ritu Apartments, A-4 Paschim Vihar, New Delhi-110063
[2]India Meteorological Department, Lodi Road, New Delhi-110003
prasadonkari123@yahoo.in, op_singh54@yahoo.com

ABSTRACT
While there were no intra-seasonal changes during southwest monsoon-2009, large intra-seasonal changes took place during southwest monsoon-2010: Two intense systems, one each over the Bay of Bengal and the Arabian Sea developed in May, i.e., during the onset phase of monsoon. No depression developed either over the Arabian Sea or the Bay of Bengal during the monsoon season. Though monsoon onset took place over the Bay of Bengal and Kerala coast around its normal date, it was delayed by 1-3 weeks in some parts of East and Central India and still monsoon covered entire country by 6th July, about 9 days earlier to its normal date. Monsoon circulation became weak, particularly from the second half of June till the end of July. It improved thereafter and became weak once again during the second half of September. The combined effect of the features of an active monsoon, as displayed in the activity of South Indian Convergence Zone (SICZ) during the period January to May-2010, and the intra-seasonal changes during the monsoon season resulted in excess rainfall over peninsular India and parts of Northwest India, below normal to deficient over the major parts of monsoon core zone comprising of Gangetic West Bengal, Bihar, Orissa, Jharkhand, Madhya Pradesh and East Uttar Pradesh and normal in the remaining areas. It has been shown that the features in the activity of SICZ as seen during the pre-monsoon months of April and May coupled with the influence of the changes which took place in Equatorial Pacific Ocean (EPO) in association with the demise of El-Nino and development of La Nina resulted in further intensification of SICZ in Southeast Indian Ocean (SEIO) and occurrence of weak cyclo-genesis in it. These factors might have been responsible for the absence of development of any depression in the Bay of Bengal, southward tilt of the eastern portion of monsoon trough and reduction in rainfall, particularly in the monsoon core zone. In spite of such large intra-seasonal changes, Long Range Forecasts (LRF) of seasonal rainfall by SICZ model were found satisfactory.

INTRODUCTION

Indian Summer Monsoon Rainfall (ISMR), which accounts for about 80% of the annual rainfall of India, has large impact on agricultural output and hence on the economic development of the country. ISMR shows large inter-annual variability. It has been shown in a recent analysis of the variation of the Gross Domestic Product (GDP) and the monsoon rainfall (Gadgil, et al., 2007) that in spite of planned developments after independence, the impact of severe droughts on GDP has remained between 2 and 5% of GDP throughout. Therefore, foreshadowing the occurrence of extreme seasons (i.e., droughts and excess rainfall) remains an important aspect of seasonal forecasting of summer monsoon rainfall. In a recent analysis of ISMR and rainfall in meteorological sub-divisions of India (numbering 36) (Prasad and Singh,2012) it has been shown that forecast for India as a whole or even for four broad homogeneous regions, each comprising of several subdivisions, can not indicate likely scenario of rainfall in a particular subdivision. Thus issuing forecast for individual subdivisions appears to be the only solution if the forecast is to be termed as 'Useful' from users' point of view. Though LRF of southwest monsoon rainfall is being issued by India Meteorological Department for more than a century, foreshadowing occurrence of extreme seasons (droughts and excess rainfall) had remained a challenging task. None of the LRF models, statistical or dynamical, could foreshadow the recent droughts of 2002, 2004 and 2009. Recently, Sadhuram and Ramana Murthy (2008) have shown high correlation between SST Anomalies (SSTA) over southeastern Arabian Sea in the preceding January and ISMR. Significant positive correlation was also reported with SSTA over northwest of Australia in the preceding February. The combined SSTA index has shown a very high correlation of 0.71 with ISMR. They have developed a multiple regression model using the combined SSTA index of the two regions as one parameter and East Asia sea-level pressure (average during February and March over the region 35°-45°N;120°-130°E having CC of 0.62 with ISMR) as another parameter. Their simple multiple regression model could foreshadow the droughts of 2002 and 2004.

Secondly, for LRF of monsoon rainfall to become one of the inputs to agricultural planning like seeds, fertilizers etc, it should be available at meteorological subdivision/district level. In this context, SICZ model proposed by Gupta and Prasad (1992, 1993) should be considered as an important development in long range forecasting of southwest monsoon rainfall in India. Recently, significant improvements have been made in SICZ model (Prasad et al., 2010a,b; Prasad and Singh, 2012). In addition to rainfall forecast for India as a whole, SICZ model provides LRF of rainfall for individual meteorological subdivisions of India and the districts of Himachal Pradesh (Prasad and Singh, 2008), Tamilnadu and Pondicherry (Prasad et al., 2010a). Verification of real time forecasts for the past 22 years, beginning from 1990 (Prasad and Singh, 2012) have shown that the model is capable of providing reasonably good forecasts of rainfall for the country as a whole and for several meteorological subdivisions. SICZ model alone could foreshadow the recent droughts in 2002, 2004 and 2009. In spite of reasonably good forecast of ISMR and rainfall in individual meteorological subdivisions of India by SICZ model, it was seen that the difference between the forecast and actual rainfall was larger than the error limit of the model (± 5 % for ISMR) in a few years, e.g., 1992,1999, 2001 and 2005. These years also witnessed intra-seasonal changes in summer monsoon circulation system over Indian sub-continent.

El Nino/Southern Oscillation (ENSO) which affects the weather worldwide is an important external forcing relating to inter-annual variability of ISMR. In an effort to understand the role of the changes in Equatorial Pacific Ocean (EPO) relating to development of El Nino/ ENSO- neutral conditions/ La Nina or vice versa in the development of intra-seasonal changes in summer monsoon circulation system over Indian subcontinent and incorporation of its impact in updating the LRF of southwest monsoon rainfall, already issued at the end of May, the authors started monitoring, on the real time basis, the changes taking place over Indian and Pacific Oceans during southwest monsoon beginning from the year 2009.

SICZ model makes use of the precursors which develop in cloud data from the equatorial regions of Indian Ocean during January-May and which could be monitored in the activity of SICZ to forecast monsoon rainfall during June-September. The methodology has been discussed in Pt I of the paper (Prasad et al. 2010b). Forecast of rainfall for India as a whole has been discussed In Part II(Prasad and Singh,2012a) and that for meteorological subdivisions in Part III (Prasad and Singh,2012b). In majority of the years, precursors seen during the period January-May continue up to the end of southwest monsoon season or even up to the end of the year. This was the case in 2009. However, in some of the years there are intra-seasonal changes in summer monsoon circulation system. This was the case in 2010. What were the causes for these intra-seasonal changes and how the forecast already issued at the end of May 2010 could be modified in June 2010 by taking into account the likely impact of the new features in the activity of SICZ which appeared during the first three weeks of June 2010 are discussed in this part of the paper.

SOUTHWEST MONSOON-2009

In the year 2009, India experienced one of the worst droughts on record when ISMR was 23% below normal. The other droughts of comparable severity had occurred in the years 1918 and 1972 when ISMR was 25 % below normal. During the year 2009, SST anomalies in Nino 3.4 region were negative till the pre-monsoon months of April-May and

Table 1: Pacific warm and cold episodes based on a threshold of ± 0.5°C for the Oceanic Nino Index (ONI). 3-months running mean of ERSST.v3 SST anomalies in the Nino 3.4 region [5°N-5°S, 120°-170°W)], calculated with respect to the 1971-2000 base period. For historical purposes El Nino and La Nina episodes are defined when the threshold is met for a minimum of 5 consecutive over-lapping seasons.

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2008	-1.5	-1.4	-1.1	-.7	-.5	-.4	-.1	0.0	0.0	0.0	-0.3	-0.6
2009	-0.8	-0.7	-0.5	-0.1	0.2	0.6	0.7	0.8	0.9	1.2	1.5	1.8
2010	1.7	1.5	1.2	0.8	0.3	-0.2	-0.6	-1.0	-1.3	-1.4	-1.4	-1.4

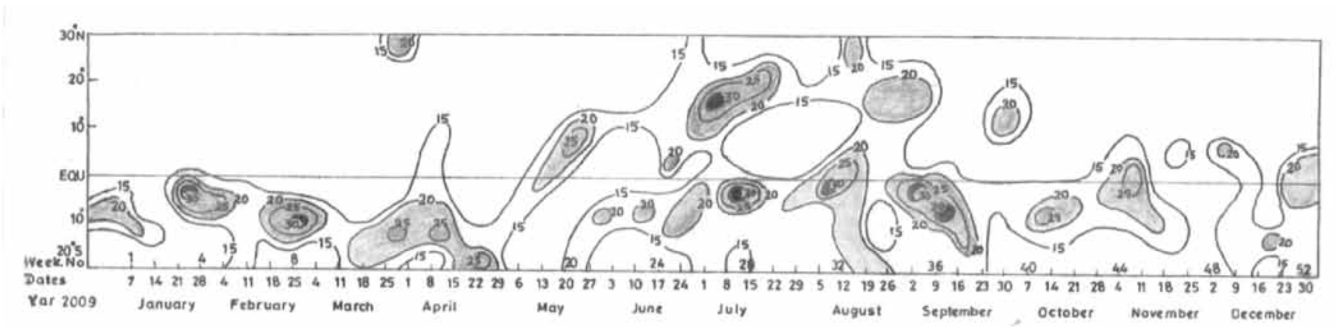

Figure 1. Zonal weekly mean cloudiness between lat. 20° S- 30° N and long. 40° E-100° E.

started becoming positive thereafter. Mild El Nino conditions developed during southwest monsoon season (Table 1). Thus the ongoing changes in EPO did not indicate development of a severe drought in India during southwest monsoon-2009. However, in Indian Ocean a severe drought signal was seen in the activity of SICZ, viz., SICZ was active for 3-4 weeks in continuation and this feature, in the activity of SICZ, was present during the period January-May (Fig.1). SICZ Activity Index (SAI) assigned in the year 2009 was 15. Accordingly the forecast ISMR for monsoon-2009 was 14% below normal. It is assumed that the assigned value of SAI could have an error of ± 2 and accordingly the model error is ± 5%. The model error is different in meteorological subdivisions. Subdivision-wise seasonal forecast for SAI=15 and 17 have been included in Table 2. The actual ISMR during the year 2009 was 23% below normal. Thus the forecast of a drought during 2009 was accurate. Though on the higher side, the quantitative forecast of ISMR was only slightly different than actual one when the model error is taken into consideration. The same was the case with the forecast in the majority of the subdivisions also (Table 2). The operational forecast for ISMR was 2 % below normal. Subdivision-wise seasonal forecasts are not available from any other LRF model for comparison. No intra-seasonal changes took place in monsoon circulation system during 2009. The characteristic features observed in the activity of SICZ during January-May continued during June-September also (Fig.1). There was no intra-seasonal change in EPO also. Slight increase in positive SST anomalies during pre-monsoon months continued during southwest monsoon season also leading to development of a mild El Nino (Table 1).

SOUTHWEST MONSOON-2010

Large intra-seasonal changes took place in monsoon circulation system and also in the activity of SICZ during southwest monsoon-2010. These changes were found to be related to the on-going changes taking place in EPO: In EPO demise of El Nino and development ENSO-neutral condition/ La Nina was taking place during summer monsoon-2010. The impact of the intra-seasonal changes, which took place over EPO, on southwest monsoon during-2010 and the performance of SICZ model during the year are discussed below.

Though SWM-2010 delivered normal rainfall for country as a whole (~102% of the normal which is

Table 2: SICZ model forecast and actual seasonal rainfall during southwest monsoon-2009

S. No.	Meteorological Subdivision	% departure of forecast rainfall		% departure of actual rainfall
		SAI=15	SAI=17	
1.	Andaman and Nicobar Islands	-15 N/MD	-19 N/MD	-5 N
2.	Arunachal Pradesh	-3 N	-5 N	-18 N
3.	Assam and Meghalaya	-3 N	-6 N	-30 D
4.	Naga., Mani., Mizo. and Tripura	-10 N/MD	-12 N/MD	-20 MD
5.	S. H. West Bengal & Sikkim	-3 N	-5 N	-22 MD
6.	Gangetic West Bengal	4 N	0 N	-15 N
7.	Orissa	-7 N	-8 N	0 N
8.	Jharkhand	-6 N	-11 N/MD	-23 MD
9.	Bihar	1 N	-4 N	-28 MD
10.	East Uttar Pradesh	-12 N/MD	-20 D	-38 D
11.	West Uttar Pradesh	-15 N/MD	-25 D	-43 D
12.	Uttarankhand	-14 N/MD	-19 N/MD	-27 MD
13.	Hary, Chandi. And Delhi	-12 N/MD	-28 D	-35 D
14.	Punjab	-13 N/MD	-27 D	-34 D
15.	Himachal Pradesh	-24 D	-32 D	-34 D
16.	Jammu and Kashmir	-11 N	-23 D	-34 D
17.	West Rajasthan	-19 MD/D	-37 D	-42 D
18.	East Rajasthan	-19 MD/D	-32 D	-31 D
19.	West Madhya Pradesh	-14 N/MD	-22 D	-27 D
20.	East Madhya Pradesh	-14 N/MD	-23 D	-33 D
21.	Gujarat Region	-15 N/MD	-30 D	-34 D
22.	Saurashtra, Kutch and Diu	-26 D	-31 D	26 E
23.	Konkan and Goa	-6 N	-10 N/MD	-17 N
24.	Madhya Maharashtra	-7 N	-13 N/MD	-2 N
25.	Marathwada	-18 MD	-27 D	-25 MD
26.	Vidarbha	-18 MD	-25 D	-32 D
27.	Chhattisgarh	-14 N/MD	-25 D	-34 D
28.	Coastal Andhra Pradesh	-14 N/MD	-21 D	-25 MD
29.	Telangan	-15 N/MD	-23 D	-35 D
30.	Rayalaseema	-4 N	-11 N/MD	2 N
31.	Tamilnadu and Pondicherry	6 N	2 N	0 N
32.	Coastal Karnataka	-9 N	-12 N/MD	1 N
33.	North Interior Karnataka	-6 N	-7 N	26 E
34.	South Interior Karnataka	-1 N	-2 N	25 E
35.	Kerala	-11 N	-12 N/MD	-9 N
36	Lakshadweep	-2 N	-5 N	1 N
India as a whole		-14 D	-19 D	-23 D

Excess (E): R/F 20% or more in sub-divisions, Normal (N): 19%- -19%, Moderate Deficit (MD): -20%- -30%, Deficient(D):-31%- -59%. Excess (E): R.F.> 10% for India as a whole, Normal (N): 10% to -10% and Deficient: -11% or less. Model error is +/- 5% for India as a whole. Model error is different for each sub-division..

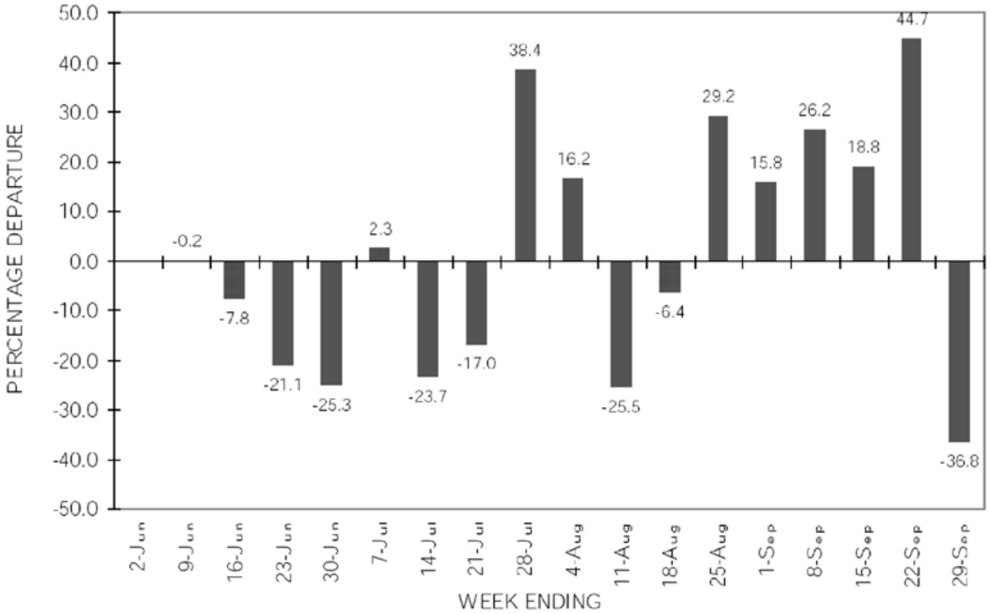

Figure 2. Week - by - Week Progress of the Monsoon Rainfall – 2010.

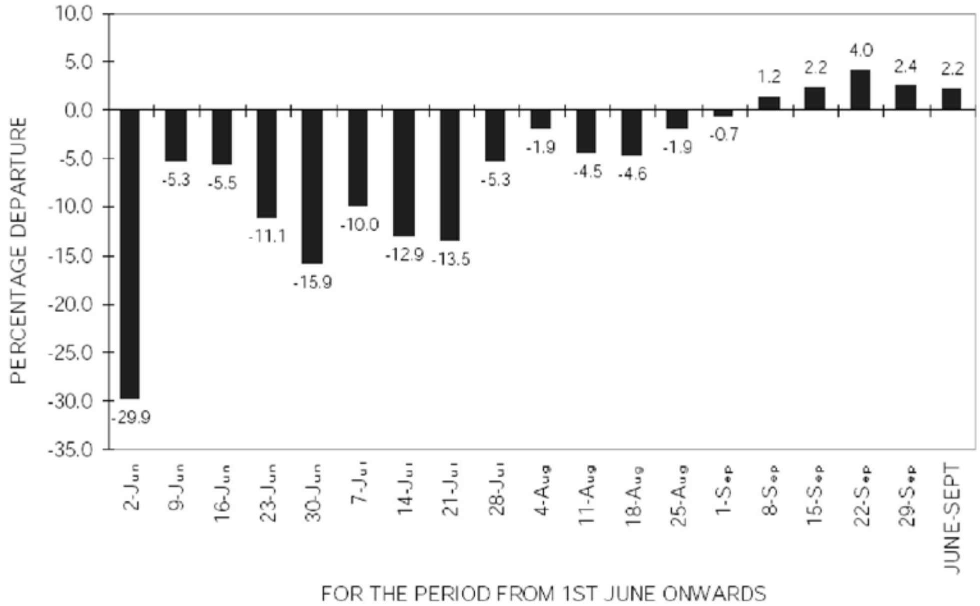

Figure 3. Week by week progress of southwest monsoon-2010 (cumulative)

89 cm) by the end of the season, weekly rainfall was on the lower side of normal during the first half of the season (June-July) (Fig. 2) except for the first and the last week of July. Rainfall deficiency, week after week, particularly in the monsoon core zone (Gangetic West Bengal, Bihar, Orissa, Jharkhand, Chhattisgarh, Uttar Pradesh and Madhya Pradesh) was a cause of concern till the situation started improving in August (Fig.3).

Monthly rainfall in meteorological sub-divisions are given in Fig.4. By the end of the season cumulative rainfall distribution in meteorological sub-divisions improved to the extent that it was 'excess' in 14, 'normal' in 17 and 'deficient' in 5 subdivisions out of 36 meteorological sub-divisions (Fig. 5). While peninsula and part of northwest India received excess rainfall, rainfall was below normal or deficient in

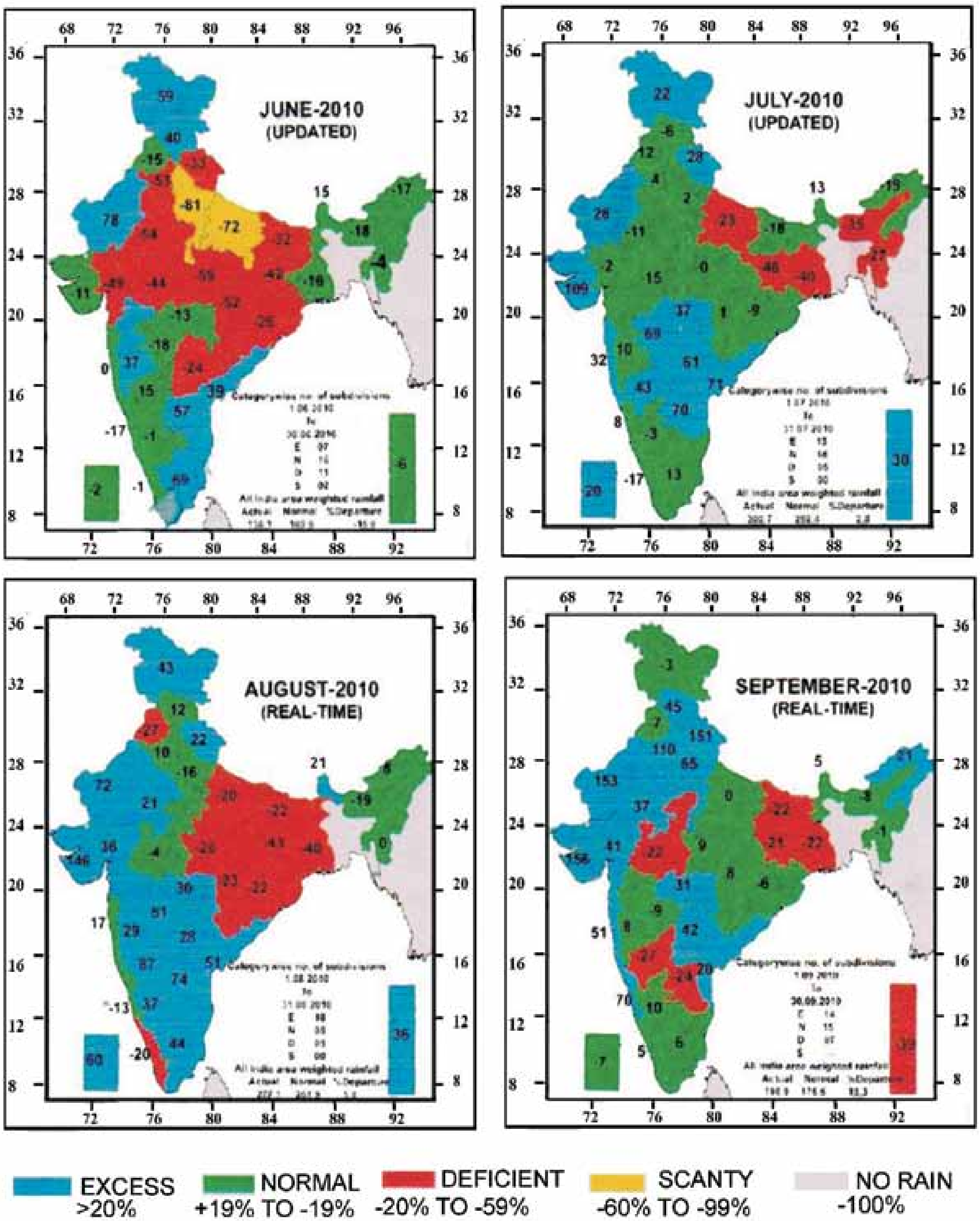

Figure 4. Subdivision-wise monthly rainfall distribution during southwest monson season-2010.

Assam and Meghalaya, Gangetic West Bengal, Bihar, Orissa, Jharkhand, Chhattisgarh, East Uttar Pradesh, East Madhya Pradesh and West Madhya Pradesh. The rainfall distribution gives an impression that SWM-2010, displayed the characteristics of an excess, a normal as well as of a deficient monsoon in different regions of India.

The cloud features over the Equatorial Indian Ocean (EIO) are monitored throughout the year and the intra-seasonal changes in monsoon circulation

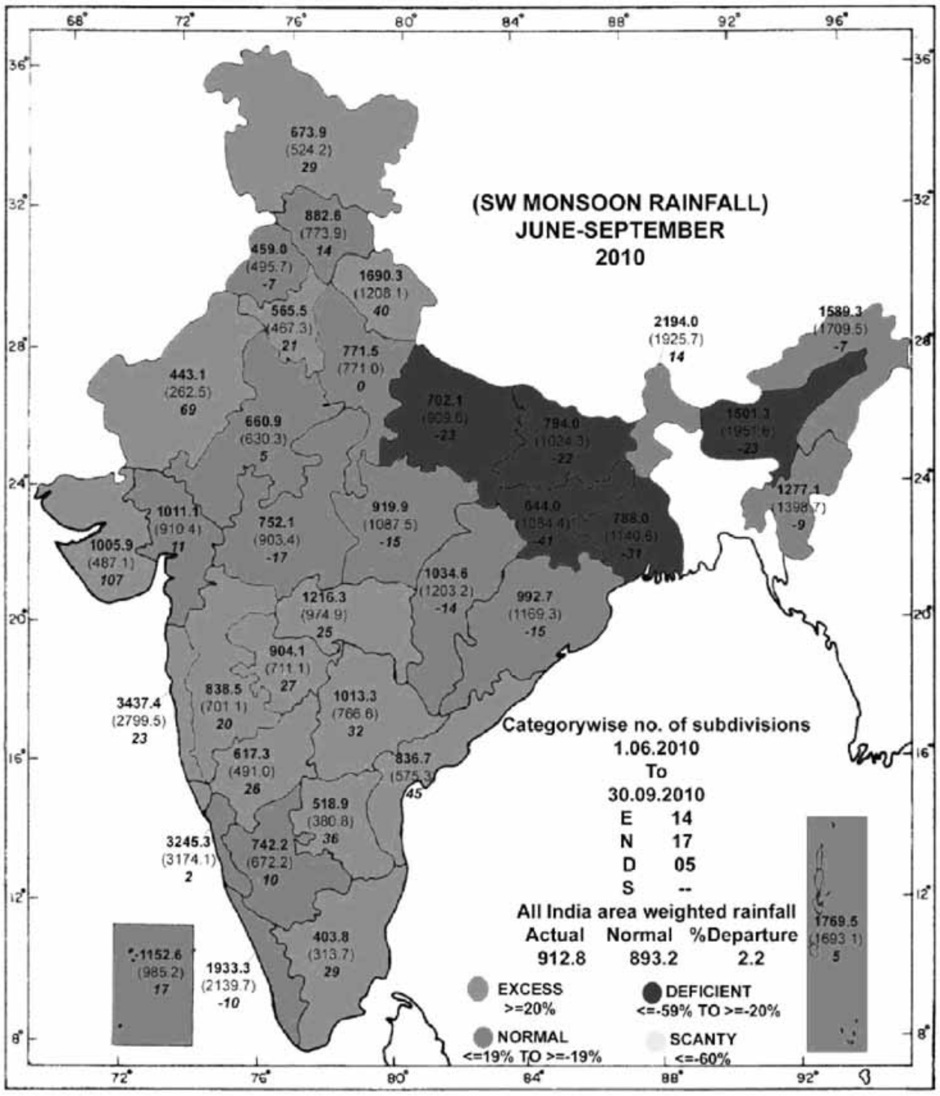

Figure 5. Subdivision-wise rainfall distribution over India during southwest monsoon season (June -September) – 2010

could be seen in the activity of SICZ. During the year 2010, there were changes in the features in the activity of SICZ from winter (January-March) to pre-monsoon months (April-May) and from pre-monsoon months to summer monsoon months (June-September). These changes were reflected in the performance of SWM-2010. The changes in the activity of SICZ, SWM-2010 and their links to the changes which took place in EPO are discussed below.

SALIENT FEATURES OF SOUTHWEST MONSOON-2010

Southwest monsoon advanced over the Andaman Sea on 17th May (IMD, 2010). Onset phase witnessed active cyclo-genesis in Bay of Bengal (development of Severe Cyclonic Storm, 'LAILA', 16-21 May) as well as in the Arabian Sea (development of Very Severe Cyclonic Storm, 'PHET', 31 May – 2 June). SWM-2010 set in over Kerala on 31st May, i.e., close to its normal date and covered the entire country by 6th July, about 9 days before its normal date (15th July). There was practically no advance of monsoon for about 2 weeks (19th-30th) in June. This caused a delay in onset of monsoon for about 2-3 weeks over Madhya Pradesh and 1-2 weeks in Uttar Pradesh. Withdrawal of monsoon from west Rajasthan commenced on 27th September where as the normal date is 1 September.

No depression formed, either over the Bay of

Bengal or the Arabian Sea or over land during the season. A total of 14 low pressure systems (2 in June, 4 each in July, August and September) formed during the season. One low pressure area of June dissipated in-situ and the other was short lived. The low pressure areas that formed over the Bay of Bengal in July (2-6 July, 6-9 July, 24-27 July and 28 July-2 Aug.) moved up to Madhya Pradesh/Rajasthan. The interval between the formation of the 2nd and 3rd low pressure areas was little more that 2 weeks (17 days). Four low pressure areas developed in August (4th-9th, 12th-14th, 23rd-27th and 30th-31st). The interval between the development of 2nd and 3rd low pressure areas was around 2 weeks (12 days). Four low pressure areas formed in September (3rd-6th, 8th-13th over land, 17th-20th; 29th-30$^{th)}$ over southeast and adjoining east central Arabian Sea. The interval between the formation of the second and the third low pressure areas and between third and fourth was 9 and 12 days respectively. Most of the low pressure areas formed over Bay of Bengal in relatively more southerly latitudes. It may be noted that the interval between the formation of the second and third low pressure areas in July, August and September was around 2 weeks. The interval between the formation of first and second and also between third and fourth low pressure areas in these months, except September, was relatively small. These aspects are discussed below in relation to the activity of SICZ.

Actual rainfall was normal (2% above normal) for the country as a whole. Cumulative seasonal rainfall from 1st June to 30th September 2010 was excess in 14 subdivisions, normal in 17 subdivisions and deficient in 5 subdivisions only. For country as a whole monthly rainfall was above LPA during July-September and below normal in June. Figs. 2 and 3 (IMD, 2010) show the rainfall received for country as a whole week-by-week and cumulative during the season. Rainfall was negative during all the weeks of June, 2nd and 3rd weeks of July and August and last week of September. The cumulative seasonal rainfall deficiency by more than 10% prevailed from the week ending 23rd June to the week ending on 21st July. The cumulative rainfall remained negative till the end of August. Thereafter it remained positive till the end of the season.

It may be noted here that there was considerable weakening of monsoon circulation for about 2 weeks in June (19th-30th) when there was no further advance of monsoon and also during July (10th -23rd) when no low pressure area developed over the Bay of Bengal. This feature repeated during August and to a lesser extent in September also. This feature is also reflected in reduction of rainfall during the period 23rd June to 21st July. Appearance of a gap of about 2 weeks in the development of low pressure areas and in actual rainfall is discussed below in relation to the activity of SICZ.

LONG RANGE FORECAST OF RAINFALL

India Meteorological Department (IMD) issued LRF of southwest monsoon-2010 rainfall for country as a whole in two-stages: (i) on 23rd April 2010 and (ii) forecast update on 25th June (Table 3). April forecast indicated normal rainfall (98% of LPA) with model

Table 3: Operational long range forecasts issued by IMD and actual rainfall during SWM-2010

Region	Period	Date of Issue	Forecast rainfall (% of LPA)	Actual Rainfall (% of LPA)
All India	June to September	23rd April	98 ± 5	102
All India	June to September	25th June	102 ± 4	102
Northwest India	June to September		102 ± 8	112
Central India	June to September		99 ± 8	104
Northeast India	June to September		103 ± 8	82
South Peninsula	June to September		102 ± 8	118
All India	July		98 ± 9	103
All India	August		101 ± 9	106
All India	August to September	30th July	107 ±7	109
All India	September	27th August	115 ± 15	113

Table 4: Long range forecast of ISMR based on SICZ Model and actual rainfall during SWM- 2010

Date	Forecast	Actual rainfall (% of normal for India as a whole)
10th Feb	A normal monsoon with seasonal rainfall for the country as a whole on the higher side of long period average (100%).	102
31st Mar	A normal monsoon with seasonal rainfall for the country as a whole on the higher side of long period average (100%).	102
31st May	A normal/excess monsoon with seasonal rainfall for the country as a whole likely to be 10% above long period average (100%). Model error ± 5%. Forecast for meteorological sub-divisions and districts of Himachal Pradesh and Tamilandu are included in Tables 5, 6 and 7.	102 Actual rainfall for Met. sub-divisions (36) and districts of Himachal Pradesh and Tamilandu are included in Tables 5, 6 and 7.
23 June	A normal monsoon with seasonal rainfall for the country as a whole likely to be 3% above long period average (100%). Model error ± 5%. Forecast for meteorological sub-divisions and districts of Himachal Pradesh and Tamilandu are included in Tables 5, 6 and 7 respectively.	102 Actual rainfall for Met. sub-divisions (36) and districts of Himachal Pradesh and Tamilandu are included in Tables 5, 6 and 7 respectively.

error of ± 5%) for country as a whole. The updated forecast also indicated a normal monsoon (102% of LPA with a model error of ± 4%) for country as a whole. The updated forecast also contained forecast for 4 broad homogeneous regions of India, i.e., Northwest India, Northeast India, Central India and South Peninsula. Forecasts for country as a whole for the second half of the season (August-September) and for September were also issued on 30th July and 27th September respectively. Table 3 includes these forecasts also. LRF of rainfall based on SICZ model are reproduced in Table 4.

SALIENT FEATURES OF THE ACTIVITY OF SICZ

Making use of satellite observed cloud data from the Indian Ocean region for the months of January-May for a period of 38 years (1972-2009), cloud features as precursors of development of excess/normal/weak southwest monsoon, have been identified (Prasad et al; 2010b). Development of an active SICZ for 3-4 weeks in continuation has been recognized as a precursor of development of a weak monsoon. In the year 2009, this feature started developing from the third week of January (Fig.1), continued till the end of the year and disappeared by the second week of January 2010. Unlike the year 2009 when main feature of the activity of SICZ remained the same till the end of the year, there were changes in the main features of the activity of SICZ in the year 2010. SICZ model's LRF for SWM-2010 were based on these changes. They are briefly discussed below.

Mean cloudiness and cloud anomalies for the period December 2009-September 2010 are given in Figs.6 and Fig.7 respectively. Considerable weakening of SICZ occurred during January and first half of February-2010. This is seen in Negative Cloud Anomalies (NCAs) dominating the zone of SICZ (Equaror-10° S). Positive Cloud Anomalies (PCAs) which developed close to but south of equator during the last week of December-2009 moved northward up to 20° N lat. Another Maximum Cloud Zone (MCZ) which developed close to equator in the last week of January-2010, after an interval of 4 weeks, also moved northward. PCAs associated with it moved as far north as 30° N. These cloud features were precursors of development of an active SWM during June-September and formed the basis of the Forecast of 10 February. SICZ remained weak during remaining days of February and March also. PCAs and NCAs developed alternatively and both had a tendency to move towards south as well as towards

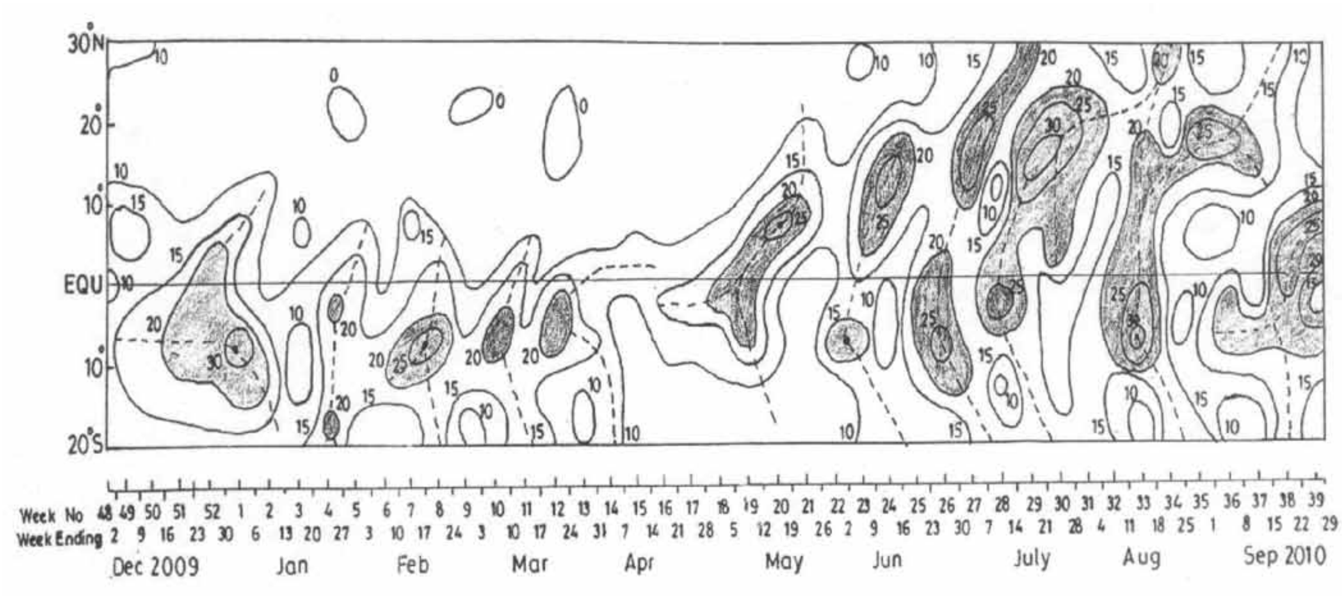

Figure 6. Weekly mean cloudiness over Indian Ocean during the period, December 2009 -September 2010.

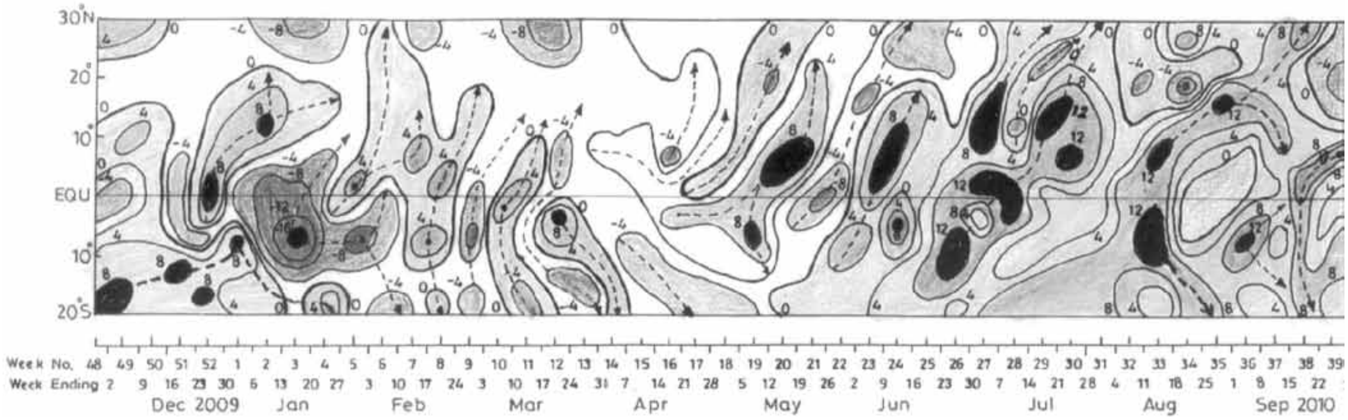

Figure 7. Weekly mean cloud anomalies over Indian Ocean during the period, December 2009-September 2010

north of equator. These features were also indicative of development of an active monsoon. As such March forecast was a repeat of February forecast.

Cloud features changed during pre-monsoon months of April and May: A weak SICZ developed in the zone of SICZ during the weeks ending on 21st and 28th April. SICZ intensified during the next 2 weeks. Thus SICZ remained active for 4 weeks in continuation beginning from the week ending on 21st April. This feature in the activity of SICZ is a precursor of a weak monsoon. LRF prepared at the end of May based on SICZ model includes quantitative seasonal rainfall for (i) country as a whole (ii) meteorological subdivisions (iii) districts of Himachal Pradesh and (iv) districts of Tamilnadu and Pondicherry. These forecasts were obtained from the regression equations developed between SICZ Activity Index (SAI) and seasonal rainfall. SAI is assigned on the basis of cloud features during the period January-May (Prasad and Singh, 2010b). The value of SAI assigned to the cloud features during the period January-May 2010 was 5 for seasonal forecast of rainfall for country as a whole and in meteorological subdivisions. How the value of SAI (=5) was arrived at is discussed here: Cloud features during January-March-2010 suggested development of an active SWM. Also they were very similar to that in the year 1983 (an excess monsoon year with ISMR being 12% above normal). SAI value for the cloud features in 1983 was 4. The other cloud feature, which appeared during the pre-monsoon months of April and May was the development of SICZ for 4 weeks in continuation. This feature developing in pre-monsoon months has been found to repeat during summer monsoon months of June-September also and results in reduction of rainfall. To account for the effect of this feature, SAI value is increased by 3 or 4 numbers (SAI is inversely related to ISMR and rainfall in meteorological subdivisions). Thus a value of 7 or 8 should have been assigned to SAI based on the cloud features which appeared during the period January-May 2010. However, it was seen that SICZ was intense (20% or more cloudiness) only during last 2 weeks out of 4 weeks period when it was active during April-May. Therefore, the value of SAI was raised by 1 number only to its value in the year 1983 making it 5 instead of 7 or 8. The value assigned to SAI for Tamilnadu and Pondicherry was 4. It was based on the cloud features identified for LRF of rainfall in Tamilnadu and Pondicherry and its districts (Prasad et al, 2010a). The forecasts for (i) meteorological subdivisions, (ii) districts of Himachal Pradesh and (iii) districts of Tamilnadu and Pondicherry have been included in Tables 5, 6 and 7 respectively.

Further change in the features of activity of SICZ was noticed during June: As expected development of an active spell of SICZ for 2 weeks (weeks ending on 23rd and 30th) took place during June. In addition there was further intensification of SICZ in South East Indian Ocean (SEIO). Intensification of SICZ took place in relation to the changes in Pacific Ocean where demise of El Nino was taking place. This aspect is discussed below. Further intensification of SICZ necessitated modification of May forecast. For updated forecast issued in June, the value of SAI was raised to 8. Reduction in rainfall was not anticipated over south Peninsula. Hence no change was made in the value of SAI for these subdivisions. As per inverse relationship between SICZ and monsoon trough, reduction in rainfall was expected around monsoon trough, i.e., over central and east India. The updated forecasts are included in Tables 4-6.

DEVELOPMENTS IN EQUATORIAL PACIFIC OCEAN

Changes taking place in EPO, particularly the development of El Nino and La Nina have drawn the attention of long range forecasters for a long time. In order to understand how the changes taking place in EPO could influence southwest monsoon circulation system, developments in EPO are being monitored since 2009. Intra-seasonal changes did not take place during SWM-2009 as was the case in the year 2010. Changes in EPO which appeared to have affected the performance of SWM-2010 are briefly discussed below.

What made southwest monsoon-2010 unique is the super-imposition of westward moving positive SST anomalies from WPO to South East Indian Ocean (SEIO) across Indonesia over the main feature in the activity of SICZ, i.e., active SICZ developing for two weeks in continuation. This created favorable conditions for further intensification of SICZ in SEIO. This was seen in the development of weak cyclo-genesis in SICZ over SEIO. Development of even weak cyclo-genesis in SEIO is uncommon during southwest monsoon and it goes against good performance of monsoon over Indian sub-continent. El Nino which was strong during January-2010, persisted during February-March. It weakened during April when the SST anomalies decreased across most of the equatorial Pacific Ocean. Climate Diagnostic Bulletins have been consulted for ongoing changes in SST, mean sea level pressure and convection anomalies. In April positive SST anomalies (+0.5°- +2.0° C) covered areas close to equator from 120° W- 40° E. Anomalies were 1-2° C between 100° E and 130° E and 40° E- 75° E. Over SEIO they were of the order of 1°C. Positive SST anomalies decreased over West Pacific Ocean (+0.5- +1.0°C) during May and increased over SWIO and also over the regions near Indonesia. Both oceanic and atmospheric anomalies reflected the demise of El-Nino in May. During June, both oceanic and atmospheric anomalies reflected development of La-Nina conditions. La-Nina conditions developed during July and strengthened during August. La Nina further strengthened during August. While SST anomalies were decreasing over equatorial central and east Pacific Ocean, they remained high over West Pacific Ocean (Fig.8). Positive SST anomalies over West Pacific Ocean propagated westward. As a consequence of this convection enhanced over Indonesia during April-June (Fig.9a-c). Convection also increased over SEIO during June and July (Figs. 9d-e). This increased convection was associated with development of weak cyclo-genesis in the zone of SICZ over SEIO. This is further discussed below.

Table 5: Forecast and actual rainfall (% departure from Normal and departure category) (E/N/MD/D/S) in Met. Subdivisions during SWM-2010

Region / Meteorological Subdivision	Forecast rainfall	Updated Forecast rainfall	Actual rainfall
Andaman and Nicobar Islands	-3 N	-3 N	5 N
Arunachal Pradesh	6 N	6 N	-7 N
Assam and Meghalaya	4 N**	4 N**	-23 MD
Naga., Mani., Mizo. and Tripura	-8 N/MD	-8 N/MD	-9 N
S. H. West Bengal & Sikkim	0 N	0 N	14 N
Gangetic West Bengal	9 N**	-2 N**	-31 D
Orissa	-1 N	-8 N	-15 N
Jharkhand	6 N**	0 N**	-41 D
Bihar	1 N**	-2 N**	-22 MD
East Uttar Pradesh	8 N**	-2 N**	-23 MD
West Uttar Pradesh	9 N	-10 N	0 N
Uttarankhand	-6 N	-12 N	40 E
Hary., Chandi. And Delhi	24 E	2 N	21 E
Punjab	21 E	0 N	-7 N
Himachal Pradesh	-1 N	-17 N/MD	14 N
Jammu and Kashmir	24 E	2 N	29 E
West Rajasthan	35 E	-3 N	69 E
East Rajasthan	13 N	-10 N	5 N
West Madhya Pradesh	9 N	-7 N	-17 N
East Madhya Pradesh	3 N	-10 N	-15 N
Gujarat Region	26 E	6 N	11 N
Saurashtra, Kutch and Diu	15 N	-5N	107 E
Konkan and Goa	7 N	0 N	23 E
Madhya Maharashtra	15 N	4 N	20 E
Marathwada	21 E	0 N	27 E
Vidarbha	7 N	4 N	25 E
Chhattisgarh	3 N	-10 N	-14 N
Coastal Andhra Pradesh	14 N	0 N	45 E
Telangan	13 N	-2 N	32 E
Rayalaseema	22 E	22 E	36 E
Tamilnadu and Pondicherry	19 N/E	19 N/E	29 E
Coastal Karnataka	14 N	14 N	2 N
North Interior Karnataka	11 N	11 N	26 E
South Interior Karnataka	12 N	12 N	10 N
Kerala	-3 N	-3 N	-10 N
Lakshadweep	9 N	9 N	17 N
% of 'Useful' forecast	86 %	86 %	

** Forecast was not in 'Useful' category. Model errors are different in sub-divisions. The relationship between SAI and rainfall is weak in the sub-divisions of NE India, West Bengal, Bihar and Orissa .

Table 6: District level forecast and actual rainfall (% departure from normal and departure category (E/N/MD/D/S) Subdivision: Himachal Pradesh

District	Forecast rainfall	Updated forecast rainfall	Actual rainfall
Bilaspur	4 N	-2 N	-5 N
Chamba	-21 D	-31 D*	-8 N
Hamirpur	28 E	5 N	-5 N
Kangra	2 N	-12 N/MD	-12 N
Kinnaur	-3 N	-24 D*	198 E
Kullu	18 E/N	3 N	100 E
Mandi	-5 N	-16 N/MD	7 N
Simla	-1 N	-17 N/MD	39 E
Sirmur	-23 D*	-34 D*	26 E
Solon	-6 N	-23 D*	12 E
Una	34 E	16 N/E	17 N
Lahol-Spiti	NA	NA	-20 MD
% of 'Useful' forecast	91%	63%	

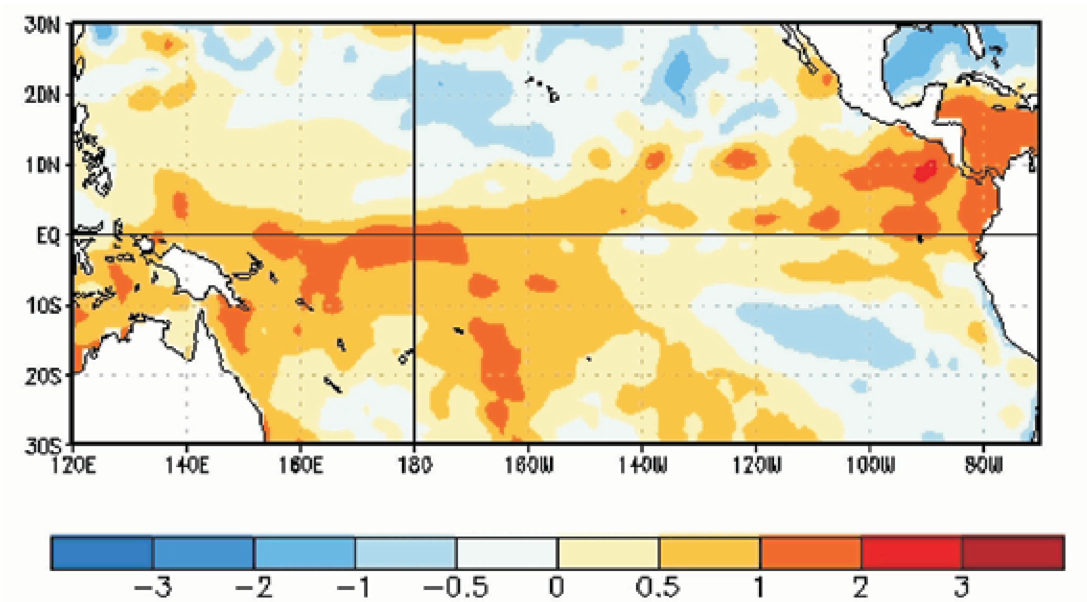

Figure 8. Sea surface temperature anomalies (°C) 28 April 2010 .

DEVELOPMENT OF WEAK CYCLO-GENESIS IN SOUTH EAST INDIAN OCEAN

Monitoring of changes in cloudiness on daily basis has shown that development of convection over SEIO (between Equator and 10°S and east of 80°E.) started on 20th June. Intense convection developed on 22nd June from 80°-100° E and Equator- 10°S. Development of weak semi-circular convective cloud mass, an indication of weak cylo-genesis, took place on 24th, 28th and 30th June between equator-10°S and 85°–100° E. The first two cloud masses did not show much movement. The third cloud mass developed near 7^{o} S 85^{o} E on 30th June. It moved southward and then westward. It showed weakening while moving southward. However, it could be tracked up to 06 UTC on 13th July 2010, when the centre was located in cumulus cloud lines near 24 S^{o} 60^{o} E.

Table 7: Districts level forecast and actual rainfall (% departure from normal) and departure category (E/N/MD/D/S). Subdivision: Tamilandu and Pondicherry.

District	Forecast rainfall	Actual rainfall
Ariyalur	7 N	-16 N
Chennai	3 N	31 E
Coimbatore	60 E	210 E
Cuddalore	14 N	-2 N
Dharmapuri	4 N	20 E
Dindigul	18 N/E	16 N
Erode	60 E	24 E
Kanchipuram	3 N	13 N
Kanyakumari	13 N	17 N
Karur	7 N	5 N
Krishnagiri	4 N	-7 N
Madurai	18 N/E	0 N
Nagapattinam	14 N	41 E
Namakkal	4 N	-3 N
Nilgiri	16 N/E	15 N
Perabmalur	7 N	9 N
Puddukottai	7 N	5 N
Ramanathpuram	15 N	91 E
Salem	4 N	45 E
Sivaganga	18 N/E	73 E
Thanjavur	7 N	15 N
Theni	18 N/E	119 E
Tirunelveli	15 N	89 E
Thirupur	60 E	24 E
Tiravallur	3 N	83 E
Tiruvannamalai	6 N	10 N
Tiruvarur	14 N	76 E
Trichy	7 N	8 N
Tuticorin	15 N	6 N
Vellore	6 N	4 N
Villupuram	6 N	21 E
Virudhunagar	18 N/E	16 N
% of 'Useful' forecast	100 %	

This system could survive for 2 weeks. Weak short lived vortices also developed in the zone of SICZ over SEIO during 20th to 23rd August and 31st August to 2nd September.

Mean monthly SST and mean sea level pressure anomalies as reported in Climate Diagnostic Bulletins published by NOAA and available on Internet were also consulted. Positive SST anomalies persisted over SEIO, between Equator and 10^{o}S east of 80^{o} E and also between 20^{o}-35^{o} S between 50^{o}-90^{o} E. Monthly mean sea level pressure anomalies in July-2010 were 1 to 3 hPa below normal over SWIO. This resulted into considerable reduction of Cross Equatorial Flow (CEF) of southeast trades into north Indian Ocean and thereby weakening of monsoon circulation during July 2010.

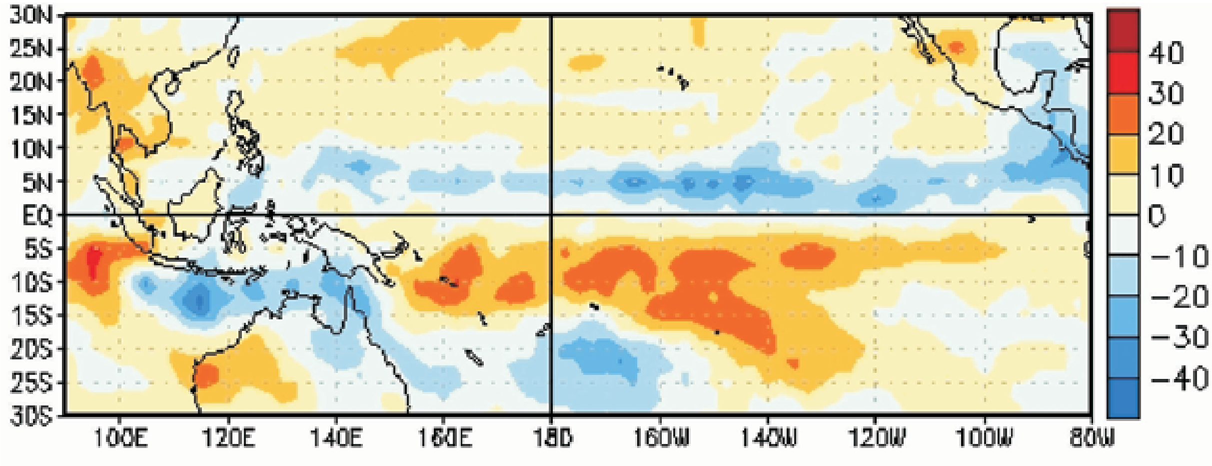

Figure 9a. Average outgoing long wave radiation (OLR) anomalies (W/m^2) for the four week period 3-28 April 2010.

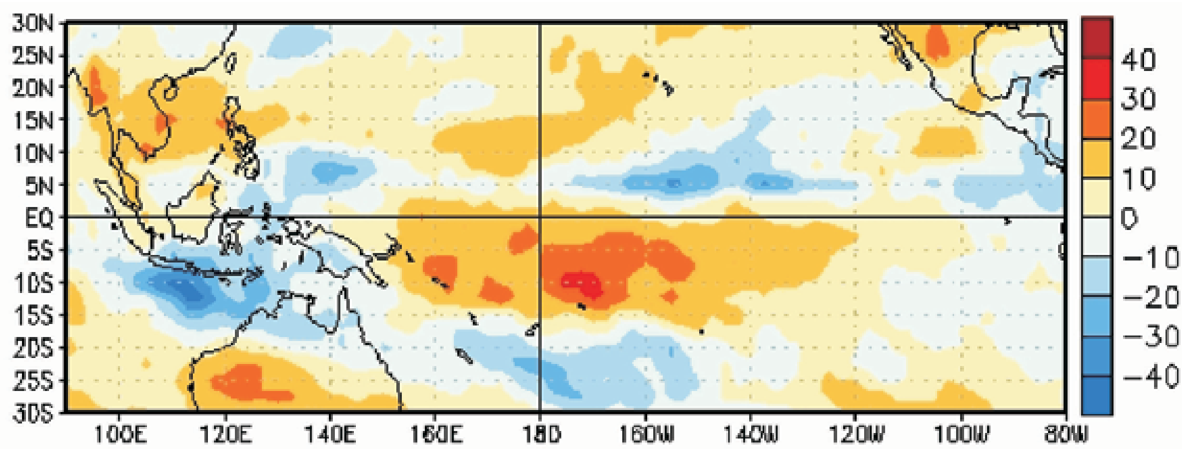

Figure 9b. Average outgoing long wave radiation (OLR) anomalies (W/m^2) for the four week period 23 April-18 May 2010

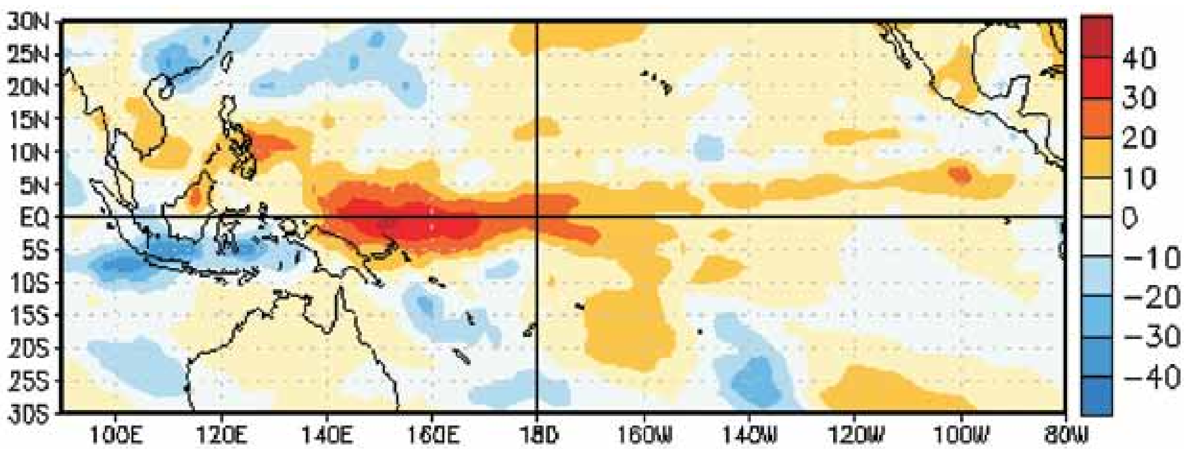

Figure 9c. Average outgoing long wave radiation (OLR) anomalies (W/m^2) for the four week period 2-27 June 2010

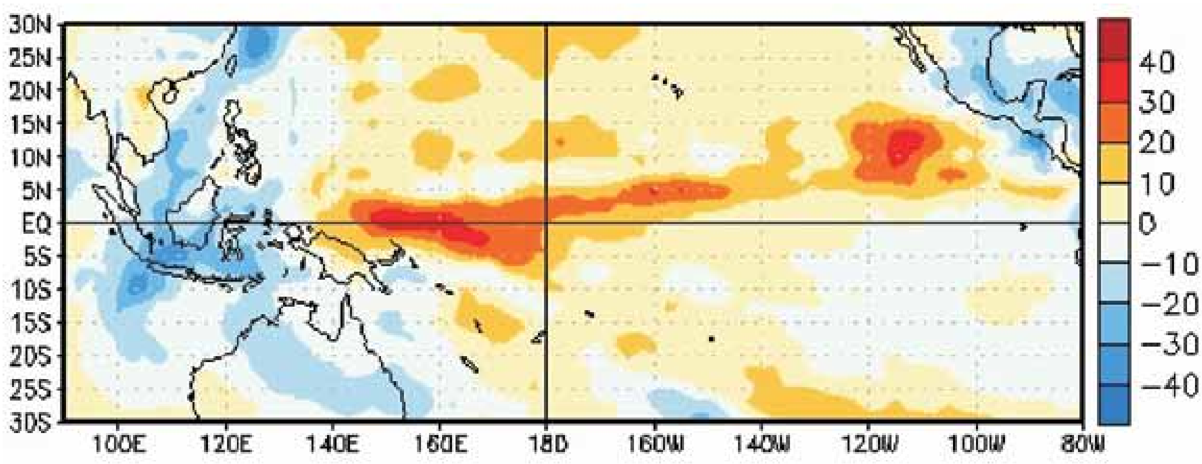

Figure 9d. Average outgoing long wave radiation (OLR) anomalies (W/m^2) for the four week period 2-27 July 2010**.**

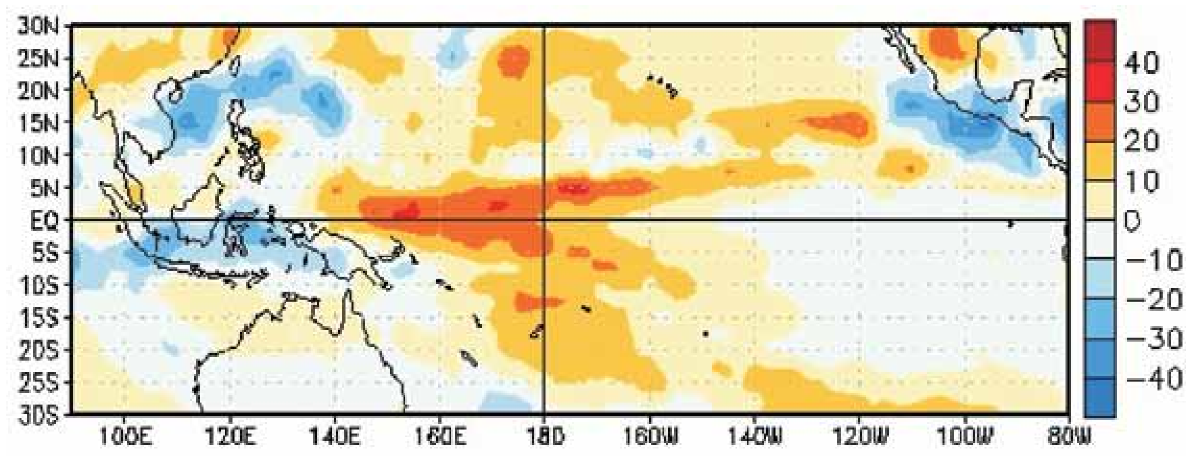

Figure 9e. Average outgoing long wave radiation (OLR) anomalies (W/m^2)for the four week period 6-31 August 2010.

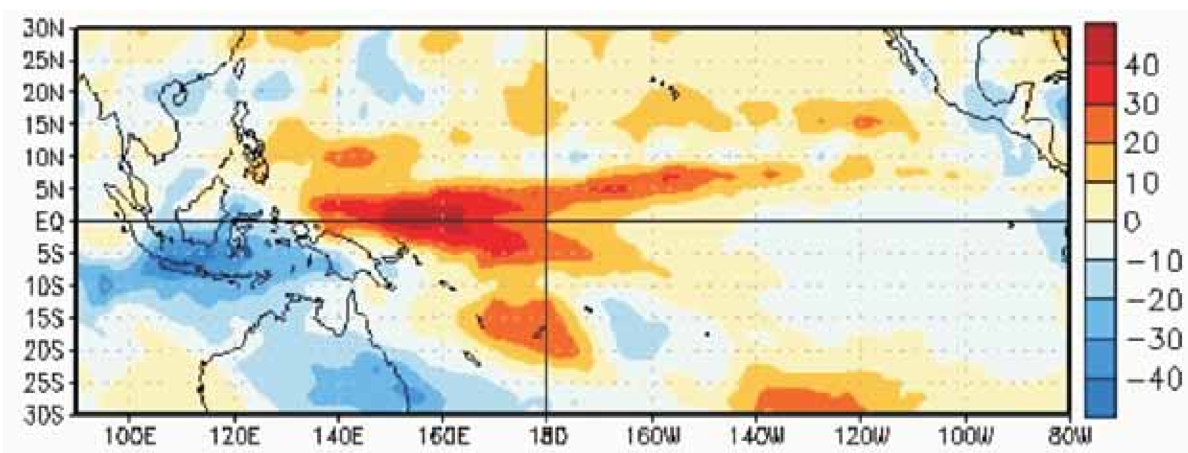

Figure 9f. Average outgoing long wave radiation (OLR) anomalies (W/m2) for the period 5-30 September 2010.

SST anomalies reduced over SIO during August and negative mean seas level pressure anomalies moved close to 90º E and further east and south over Indonesia and SW Pacific Ocean. Convection decreased in the zone of SICZ over SEIO (Fig. 9e). During September-2010, SST anomalies were of the order of 0 to +1.0º C over most parts of SIO except in SEIO where they were of the order of +0.5ºC - + 2ºC. Pressure anomalies were of the order of 0 – 1 hPa above normal up to 20º S lat. and west of 75º E. Over the rest of SIO they were 1 to 3 hPa below normal and up to 5 to 7 hPa below normal between 30º-40ºS and 50º-65ºE. Convection increased in the zone of SICZ over SEIO (Fig. 9f).

It follows from the discussions in this section that development of weak cyclo-genesis in SEIO during the second half of June till the second half of July-2010, the period which witnessed reduction in rainfall over Indian subcontinent, occurred in association with the changes in west Pacific Ocean related to the demise of El Nino and development of ENSO-neutral conditions/La Nina.

CONCLUSIONS

Intensification of SICZ for two weeks in June and July occurred as a result of westward propagation of positive SST anomalies resulting in enhanced convection over Indonesia and South East Indian Ocean. The changes in Equatorial West Pacific Ocean were related to the demise of El Nino and development of ENSO neutral conditions/La Nina. Assigning of SICZ Activity Index (SAI) on the basis of cloud features during the period January-May, and its modification based on the cloud features during the first 3 weeks of June were able to capture the characteristic features of Southwest Monsoon-2010. In spite of large intra-seasonal changes, performance of SICZ model, in producing long range forecasts of rainfall, was quite satisfactory.

ACKNOWLEDGEMENT

The authors thank the reviewers for their valuable comments. One of the authors (OP) would like to record his sincere gratitude to his Ph.D. supervisor, Prof. P. N. Belov and his colleagues at the Department of Meteorology and Climatology, Moscow State University, Moscow (Russia) for their keen interest in the studies of monsoon rainfall in India.

REFERENCES

Gadgil, S., Rajeevan, M. and Francis, P.A.,2007, Monsoon variability: Links to major oscillations over the equatorial Pacific and Indian oceans, Current Science, 93,182-194.

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

Gupta, G. R. and Prasad, O,1993, Southern hemispheric equatorial trough model of long range forecast of monthly rainfall, Hydrology Journal,16, 49-76.

India Meteorological Department, 2010, ' Southwest monsoon-2010 End of season Report'.

NOAA, 2010, 'ENSO Diagnostic Discussion' April-October-2010 and 'Climate Diagnostic Bulletin' April-September 2010.

Prasad, O. and Singh, O. P.,2008, District level long range forecast of seasonal rainfall during southwest monsoon, Vayu Mandal, 34, 51-56.

Prasad, O, Singh, O. P. and Subramanian, S. K., 2010a, ' Seasonal forecast of southwest monsoon rainfall-District level', J. Ind. Geophys. Union, 14, 93-114.

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

Prasad, O. and Singh, O. P., 2012, 'South Indian Convergence Zone model- A new approach to seasonal forecasting of summer monsoon rainfall in India ', Pt. II: Forecast for India as a whole, J. Ind. Geophys. Union, 16, 1-10.

Prasad, O. and Singh, O. P, 2013, 'South Indian Convergence Zone model- A new approach to seasonal forecasting of summer monsoon rainfall in India ', Pt. III: Forecast for meteorological subdivisions, J. Ind. Geophys. Union, 17, 75-91.

Sadhuram, Y. and Ramana Murthy, T.V., 2008, Simple multiple regression model for long range forecasting of Indian summer monsoon rainfall, Meteorol. Atmos. Phys., 99,17-24.

Manuscript received: November,2012; accepted: March,2013