MAUSAM, **64**, 4 (October 2013), 687-698

551.553.21 : 551.513.5

Large scale aspects of the monsoon-2011

Relevant to the objectives of the CTCZ

D. R. SIKKA, C. S. TOMAR*, S. I. LASKAR*, SUMAN GOYAL* and AJIT TYAGI**

Mausam Vihar, Delhi – 110 051, India

**India Meteorological Department, Lodi Road, New Delhi – 110 003, India*

***Ministry of Earth Science, Lodi Road, New Delhi – 110 003, India*

(*Received 29 March 2012, Modified 18 February 2013*)

e mail : cstomar2002@gmail.com

सार – भारत में ग्रीष्मकालीन मानसून के दौरान सिनॉप्टिक और उप–मौसमी उतार चढ़ावों को समझने के लिए वर्ष 2011 में महाद्वीपीय उष्णकटिबंधीय अभिसरण क्षेत्र (सी.टी.सी.जेड.) के नाम से भारतीय वायुमंडलीय–समुद्री विज्ञान समुदाय ने एक फील्ड कार्यक्रम आयोजित किया। इस कार्यक्रम का एक उद्देश्य मानसून के सिनॉप्टिक और अंतरा–मौसमी उतार–चढ़ावों से संबंधित बृहतमान परिसंचरण के क्रमिक विकास के बारे में जानकारी प्राप्त करना भी रहा है। इस शोध पत्र में मानसून 2011 के समय बड़े पैमाने पर हुए उतार–चढ़ावों के बारे में भी बताया गया है। वर्ष 2011 में मानूसन में मौसम की लगभग सामान्य वर्षा हुई तथापि उप–मौसमी मान पर जून माह में अच्छी वर्षा हुई, तत्पश्चात जुलाई माह में कम वर्षा हुई ओर फिर अगस्त माह के आरंभ से लेकर सितंबर माह के अंत तक फिर से अच्छी वर्षा हुई। मौसम के पूर्वार्द्ध में करीब–करीब न्यूट्रल ला–निना स्थितियाँ बनी। तथापि अगस्त माह से लेकर सितंबर माह के अंत तक भूमध्यरेखीय पूर्वी प्रशांत महासागर में समुद्र सतह तापमान (एस.एस.टी.) सामान्य से कम (ला–निना स्थितियाँ) में परिवर्तित हो गए। हालांकि गंगा के मैदानी भागों में निम्न क्षोभमंडल पर समुद्र की तरफ से आने वाली वायु का प्रवाह बना, पर पूरी ऋतु में वायु विलय लोड सामान्य से बहुत कम बने रहे। इस शोध पत्र में सिनॉप्टिक के विभिन्न पहलु, प्रशांत महासागर में एस.एस.टी के सुदूर प्रभाव से संबंधित मानसून के उपमौसमी उतार–चढ़ावों तथा भारतीय समुद्री द्विध्रुव (आई.ओ.डी.) के स्थानीय प्रभाव पर विचार–विमर्श किया गया। इसके साथ–साथ प्रचालनात्मक सांख्यिकीय मौसम प्रागुक्ति (एन.डब्ल्यू.पी.) निदर्शों, यूरोपीय मध्य अवधि मौसम पूर्वानुमान केन्द्र (ई.सी.एम.डब्ल्यू.एफ.), भूमंडलीय पूर्वानुमान प्रणाली (जी.एफ.एस.) और मौसम अनुसंधान और पूर्वानुमान (डब्ल्यू.आर.एफ.) के निष्पादन पर भी विचार–विमर्श किया गया। सी.टी.सी.जेड. आंकड़ों का उपयोग करते हुए मानसून 2011 के निष्पादन के आधर पर आगे किए जाने वाले अनुसंधान के कई क्षेत्रों के विषय में भी सुझाव रखे गए।

ABSTRACT. Indian atmosphere-ocean science community organised a field programme known as Continental Tropical Convergence Zone (CTCZ) during 2011 to understand the synoptic and sub-seasonal fluctuations of summer monsoon over India. One of the objectives of the programme was to understand the evolution of the large scale circulation in relation to synoptic & intra-seasonal fluctuations of the monsoon. The paper addresses the large scale fluctuations of Monsoon-2011. The Monsoon-2011 performed very close to the normal rainfall of the season. However, on the sub-seasonal scale its performance was good during June, became deficient during July and it recovered from the beginning of August to the end of September. The early part of the season was accompanied by near neutral La-Nina conditions. However, sea surface temperatures (SSTs) in the Equatorial Eastern Pacific Ocean shifted to below normal (La-Nina conditions) from August to the end of September. As the Gangetic Plain was swept by marine origin air stream in the lower troposphere, the aerosol load remained much below the normal during the entire season. The paper discusses different aspect of synoptic, sub-seasonal fluctuations of monsoon in relation to remote forcing of the SSTs in the Pacific and the local forcing of the Indian Ocean Dipole (IOD). Also the performance of the operational numerical weather prediction (NWP) models: European Centre for Medium-Range Weather Forecasts (ECMWF), Global Forecast System (GFS) and Weather Research and Forecasting (WRF) is discussed. Several areas of further research using CTCZ data are also suggested based on the performance of the Monsoon-2011.

Key words – CTCZ, Large scale fluctuations, SST, IOD, ENSO, MCZ, Aerosol loading, NWP models.

1. Introduction

Continental Tropical Convergence Zone (CTCZ) is a field programme to understand large scale processes that occur in different phases of the summer monsoon season (June to September) over India. These processes are linked to the coupled regional atmosphere ocean-land coupled system of the regional monsoon. The sub-programmes of the CTCZ are organised with respect to atmosphere-ocean processes, monsoon cloud system,

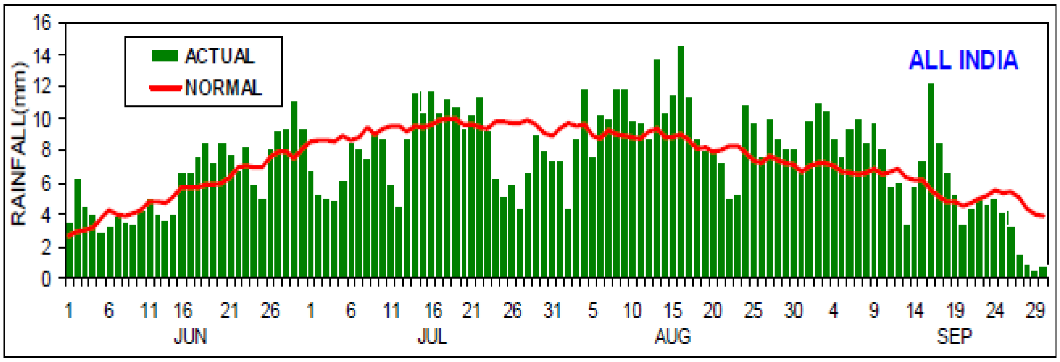


Fig. 1. Daily rainfall (mm) time series on All-India area weighted basis for the monsoon-2011

monsoon and land-surface processes which include hydrological processes, aerosol and monsoon (CTCZ Science Plan, MoES, 2011).

The pilot phase of the CTCZ took place in 2009 monsoon season which was a major drought season over India (Sikka *et al*., 2010). The program is designed to continue up to 2012 or 2013 and the first field phase campaign in this series occurred in the 2011 season. Monsoon-2011 rainfall was very close to the normal (+2% of the long period average). This report is focused on the large scale fluctuations of the Monsoon-2011 (Mazumdar *et al*., 2012) rainfall under different synoptic scale and sub-seasonal processes. Even though there was concern till mid-July about the overall performance of the seasonal rainfall; particularly as the official long range monsoon forecast by the India Meteorological Department (IMD) was -5% (below normal category in 5-stage category scale) but the season ended with normal category (+ 2% of the normal). The paper analyses the synoptic entities and the regional and global evolution of atmosphere-ocean (IOD and El Nino-Southern Oscillation (ENSO) modes) as well as the lack of aerosols load over the Indo-Gangetic (IG) Plain particularly in August and September during which period monsoon lower tropospheric easterlies of marine origin over the Bay of Bengal, prevailed over the IG Plain.

Section 2 deals with the important features of Monsoon-2011and maximum cloud zone (MCZ), Madden–Julian oscillation (MJO) and behaviour of monsoon clouds over northern & southern parts of Bay of Bengal are discussed in section 3. Broad aspects of IOD and ENSO are discussed in section 4. Effect of aerosol loading on Monsoon-2011 is discussed in section 5. Section 6 gives the performance of the IMD's operational weather forecast models in the season. Section 7 compares the Monsoon-2011 with the Monsoon-2010 and section 8 provides conclusions of the study.

2. Main features of the monsoon-2011

Details about the evolution of the monsoon are available in a few IMD publications such as the (Sikka, 2012) monsoon summary published in Mausam (Mausam, 2012) and Monsoon Report (IMD's Monsoon Report, 2011). Here we summarise the main features mentioned in the above two reports. The monsoon onset over Kerala coast occurred on 29th May, about 2 days earlier than normal. This took place with the formation of an off-shore trough across Kerala-Karnataka coast which persisted for unusual long period and moved slowly northward bringing the monsoon onset. In the southern portion of the trough the rain at the time of onset was heavy and to its north the rain was light thus creating the usual soil moisture gradient between the zone of onset and advance. Recently Krishnamurthy *et al*. (2011) have stressed the contribution of light rain in advance of monsoon which facilitates monsoon advance as a consequence of soil moisture feedbacks.

Even though no onset cyclone or depression formed off Kerala-Karnataka coast in Mosoon-2011, the moisture incursion in an organised way continued to maintain the onset phase as a result of transient disturbances in the lower troposphere. The SSTs off the west coast had not cooled abruptly as the winds over the south-east Arabian Sea & off Karnataka coast were weak because of the presence of the off-shore trough and absence of intense monsoon onset over Kerala. A low pressure area formed over north-east Arabian Sea on 6th June which extended the monsoon to Konkan coast. Formation of a depression (14th-23rd June) over Bay of Bengal and its movement over eastern & central India lasting for 8-10 days over the Gangetic Plain facilitated the advance in a regular manner. This was responsible for the monsoon advancement up to Delhi by 26th June. For the period between 1st to 30th June, there were 20 days when a low pressure system (LPS)

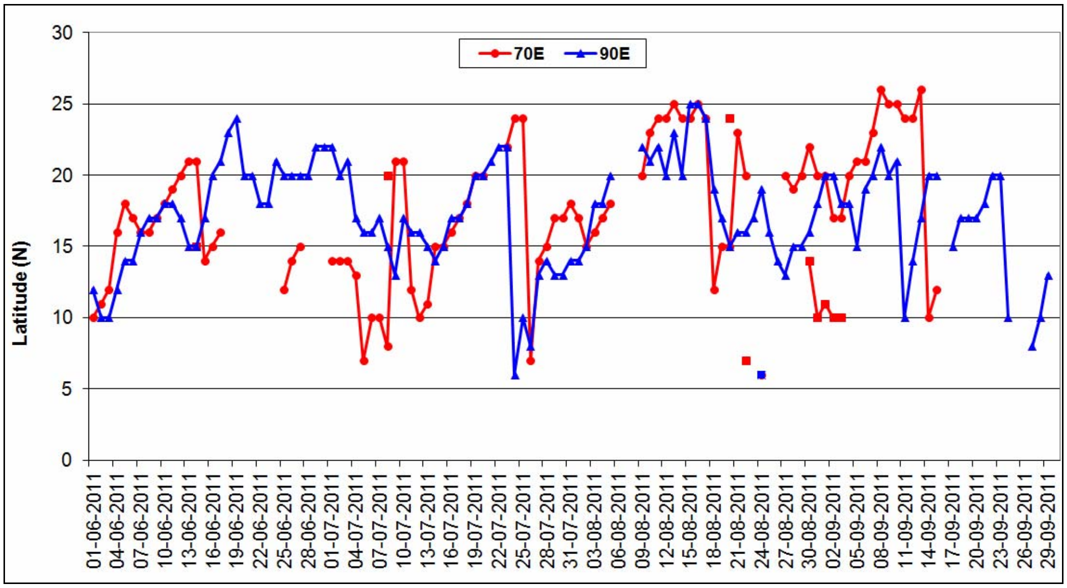


Fig. 2. Daily fluctuations of MCZ along the two longitudes 70º E (red line) and 90º E (blue line) from 1st June to 30th September 2011

existed within the core monsoon region and thus influenced the onset & its advance process.

In the peak phase of monsoon, which covered 6th July to 20th September (76 days), ten LPSs had formed and moved inland, lasting for total 60 days of peak period. Four LPSs formed in overlapping manner. Five of the LPSs were long lasting with life span of 7 to 10 days. This led to a long period of good monsoon rainfall activity from the end of July to mid-September, which was sustained by a regular formation of LPSs in the Bay of Bengal, Arabian Sea and on land too. This maintained the oscillations of the monsoon trough within its normal regime. In this period the monsoon rainfall for the country as a whole overcame the deficit of July and even entered into slightly positive departure from the normal by 20th September. This remarkable recovery from the beginning of August was the most important feature of Monsoon-2011. Fig. 1 (IMD's Monsoon Report, 2011) shows the day to day rainfall activity for India as a whole for Monsoon-2011. Rainfall remained below the normal for extended spells during 1st and 2nd week of July and again from 4th week of July to the beginning of August 2011.

Withdrawal process of monsoon from Northwest (NW) India was delayed as two overlapping LPSs formed off Odisha coast in the first fortnight of September (13th and 17th September) maintained easterly low level (850 hPa) flow over the Gangetic Plain up to Punjab. With the weakening of the low over southern Pakistan on 14th September and Bihar on 19-20th September, the stage was set for the beginning of the withdrawal process. However, another low pressure area formed over the NW Bay of Bengal on 19th September which intensified into a depression on 22nd September. The depression weakened on 24th September but remnant low continued upto 27th September and disappeared over Sub-Himalayan West Bengal on 27th September. Associated with this disturbance, rains were only confined to the zone of the disturbance. Rains had stopped over most parts of the NW India on 21st September. The weakening of this last LPS of the season lead to the withdrawal of the monsoon from NW India which continued over the central Gangetic Plain and the adjoining Western & Central India by the end of September. For the national capital - Delhi, the monsoon had arrived by 26th June and withdrew from this area on 24th September. Thus, the season over Delhi region lasted for over 90 days against the normal expectation of about 78 days. The extra 12 days or so of the prevalence of the rains over NW India and the continued fluctuations of the monsoon trough near its normal position from mid August to mid September were chiefly responsible for +2% departure of rainfall for the 2011 monsoon season over the country scale. Overall during the season 14 LPSs (4 depressions and 10 low pressure areas) formed during the season (4, 3, 4 and 3 LPSs during June, July, August and September respectively) which is about the normal.

3. Maximum Cloud Zone (MCZ)

Following the method used by Sikka and Gadgil (1980), Fig. 2 shows the latitude of the MCZ at two longitudes 70° E and 90° E from 1st June to 30th September 2011. The first northward moving phase of the

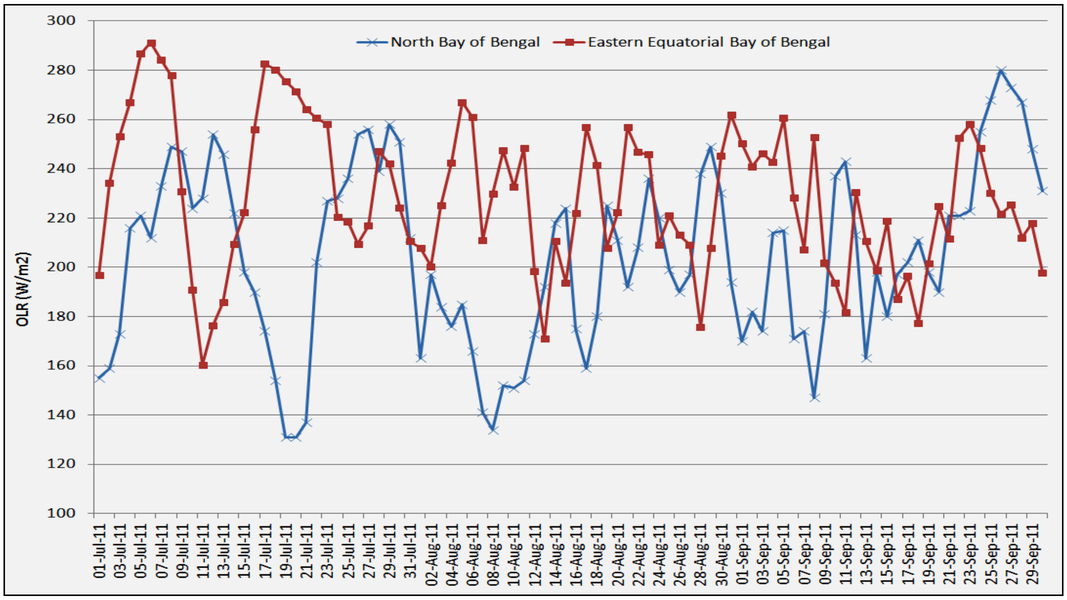


Fig. 3. OLR (W/m^2) over north Bay of Bengal (blue line) and eastern equatorial Bay of Bengal (red line) during July, August and September 2011

MCZ which was responsible for the onset of monsoon, lasted between 26th May to 30th June with peaks at 2nd June, 17th - 20th June and 26th to 30th June. The second mid-season northward moving episode of MCZ occurred between 26th July to 15th August and after that MCZ fluctuated within the monsoon zone till the monsoon withdrawal process began by 21st - 22nd September. The first episode of MCZ was of 35 days duration and the second lasted for 19 days only. The interval between the first and the second episode was about 60 days and not the usual 30-40 days. The larger interval between the first and the second phase had led to the concern about the proper evolution of monsoon by mid-July.

3.1. *Monsoon cloud system*

Monsoon cloud system includes the very large cloud clusters/bands extending over 1000-2000 km in extent to the south of the monsoon trough under active conditions and isolated cloud clusters with diameters 100-300 km embedded within the monsoon trough. The most active convection in an organised way occurs over North Bay of Bengal centred over block 18-22° N and 88-92° E. Another area of active convection lies over the eastern equatorial Bay of Bengal centred around 4° N - 4° S and 88 - 92° E. The convection over these two regions often fluctuates in a dipole manner such that when it is deeper and more organised near North Bay of Bengal, it is weak or absent over the eastern equatorial Bay of Bengal. To understand same fluctuations we have obtained the average daily outgoing longwave radiation (OLR) over the two regions. Fig. 3 shows the plots of these two regions. The active spell over the North Bay of Bengal and those over eastern equatorial Bay of Bengal can be observed to fluctuate in opposite way in several spells in the plot. There is a scope to further understand these fluctuations in terms of cloud top temperatures and the size of such deep clouds systems which are usually precipitating types.

3.2. *Madden-Julian Oscillations (MJO) and monsoon 2011*

There are studies (Pai *et al*., 2009) which shows the influence of eastward moving large scale low frequency convective episodes in the near equatorial Indian Ocean on the monsoon intra-seasonal oscillations. These low frequency oscillations caused by the Madden-Julian Oscillations sometime trigger the northward moving convective episodes over along 70.0° E to 90.0° E. Wheeler and Hendon (2004) have introduced an MJO phase diagram to diagnose the activity of MJO. According to them if the MJO is in phase 2 or 3 of its life cycle it promotes organisation of convection over the monsoon region and overlapping formation of LPSs. Fig. 4 shows that in Monsoon-2011 the activity of the MJO for the Indian Ocean was pronounced with high amplitude during August. It also lay in Indian Ocean in the first half of September with low amplitude. Thus the MJO fed the monsoon convection over the Indian Ocean area with overlapping formation of LPSs which maintained the good performance of rains over India during August and September.

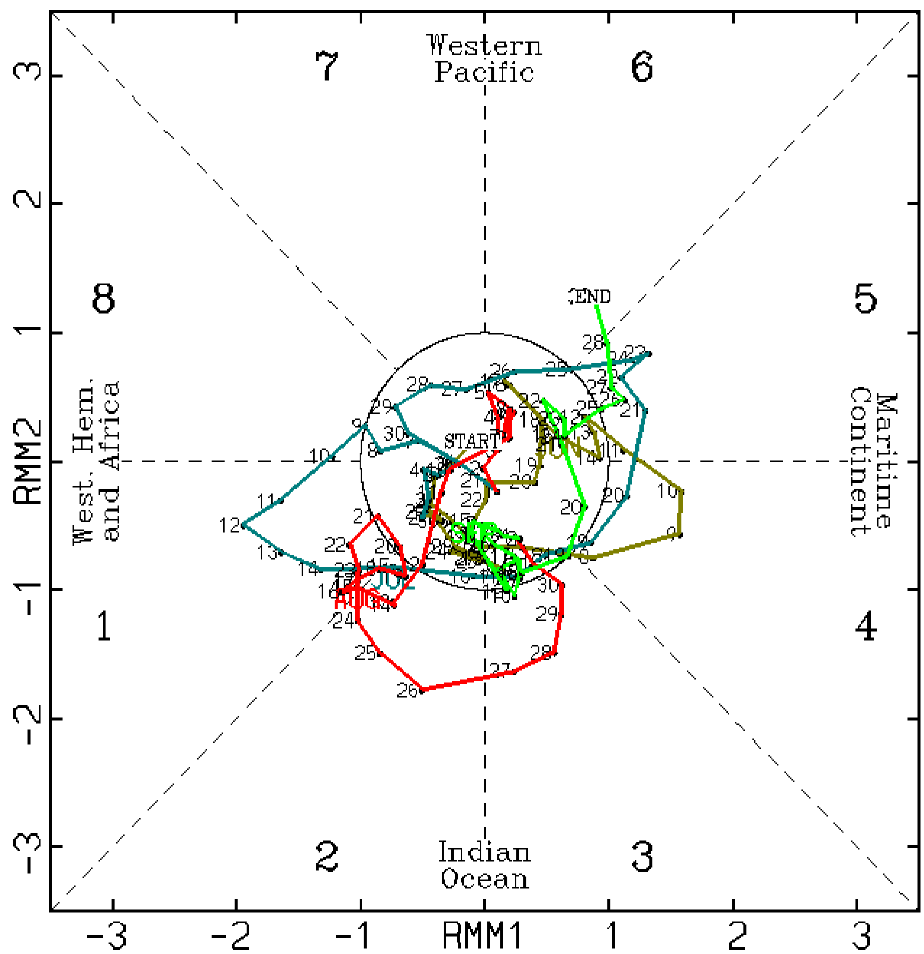


Fig. 4. RMM1, RMM2 phase space for Monsoon-2011 (June to September). Light green line represents June, blue for July, red for August and dark green line for September

4. large scale features over the eastern equatorial pacific and the eastern equatorial Indian ocean (ENSO and IOD modes in relation to monsoon-2011)

It is now well known that the monsoon has linkage with SSTs over the central & eastern equatorial Pacific through Monsoon-ENSO connections. Warmer equatorial Pacific Ocean (El Nino conditions) suppresses monsoon performance and colder SSTs in the same region (La Nina conditions) favour good performance of monsoon (Sikka, 1980; Rasmusson and Carpenter, 1983). Similarly, the IOD (Saji *et al*., 1999; Webster *et al*., 1999) has also been linked with performance of monsoon over India. For the IOD mode, if the eastern equatorial Indian Ocean has colder (warmer) SSTs and western has warmer (colder) SSTs, IOD promotes good (poor) monsoon.

In the beginning of the season, SST in the central equatorial Pacific (Nino 3.4 & Nino 3) was in warming tendency (Fig. 5). However, El Nino 3.4 index remained within the near-neutral condition throughout the season. In August the tendency of the index turned to negative but La Nina conditions did not get firmly established. The IOD mode also did not show any specific tendency for an extreme event. Thus there was no abnormal signal from the large scale remote (ENSO) or local (IOD) ocean-atmosphere system. The weekly IOD Index (Fig. 6) available from Japan had remained negative or slightly positive from January 2011 to July 2011. However, the IOD Index became moderately positive between August to September. This occurred along with the tendency towards La Nina conditions in the Nino 3.4 and Nino 3 of the central equatorial Pacific. There is a possibility that change over to positive IOD Index and La Nina conditions

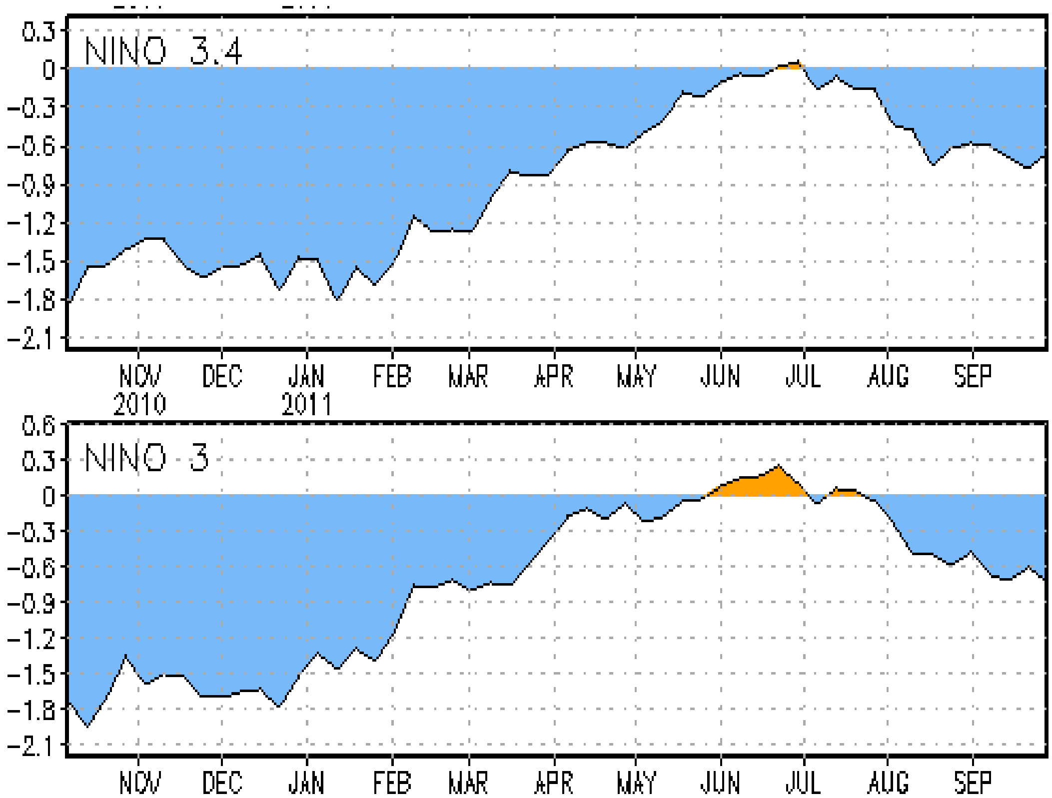


Fig. 5. Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño 3 (5°N - 5°S, 150° W - 90° W) and Niño-3.4 (5° N - 5° S, 170° W - 120° W). (*Source* : Climate Prediction centre, NOAA, USA)

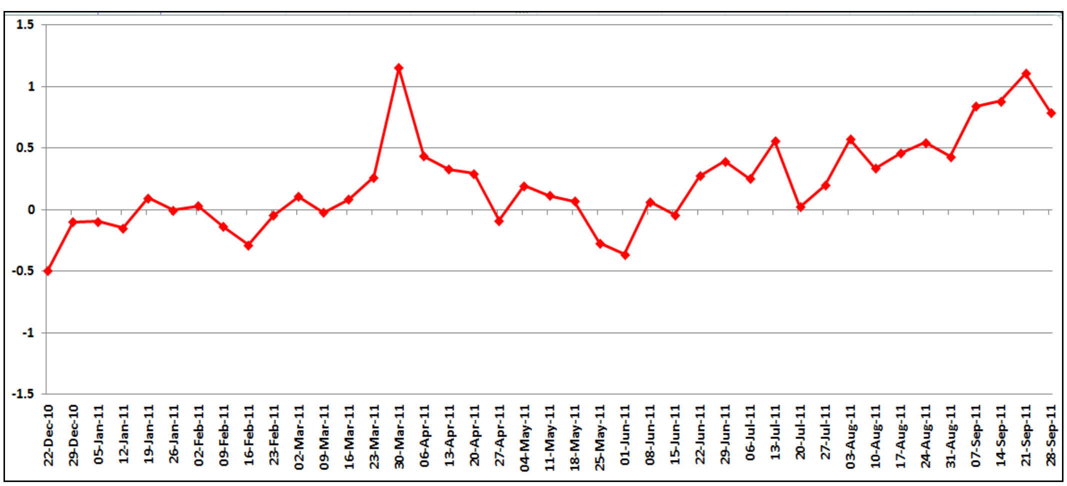
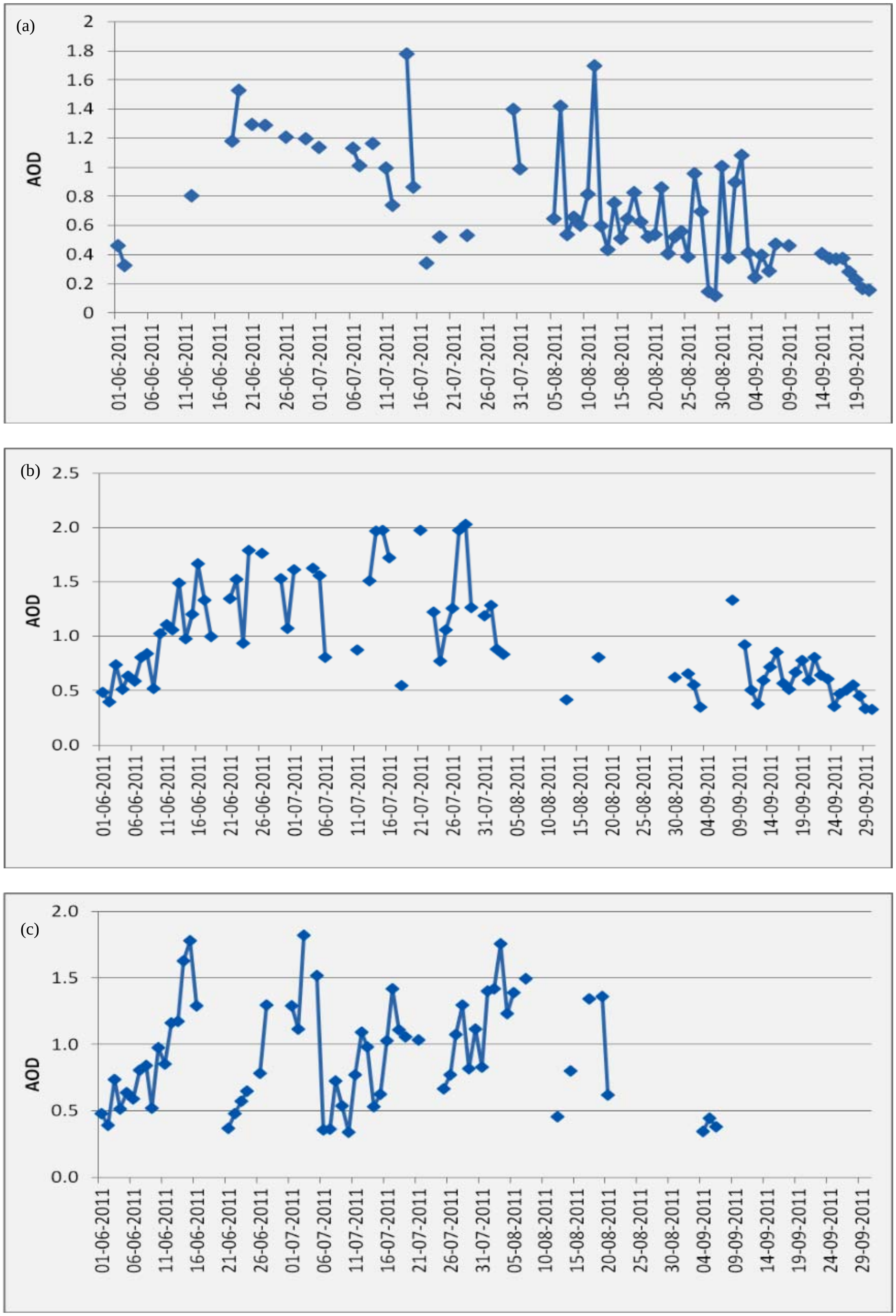
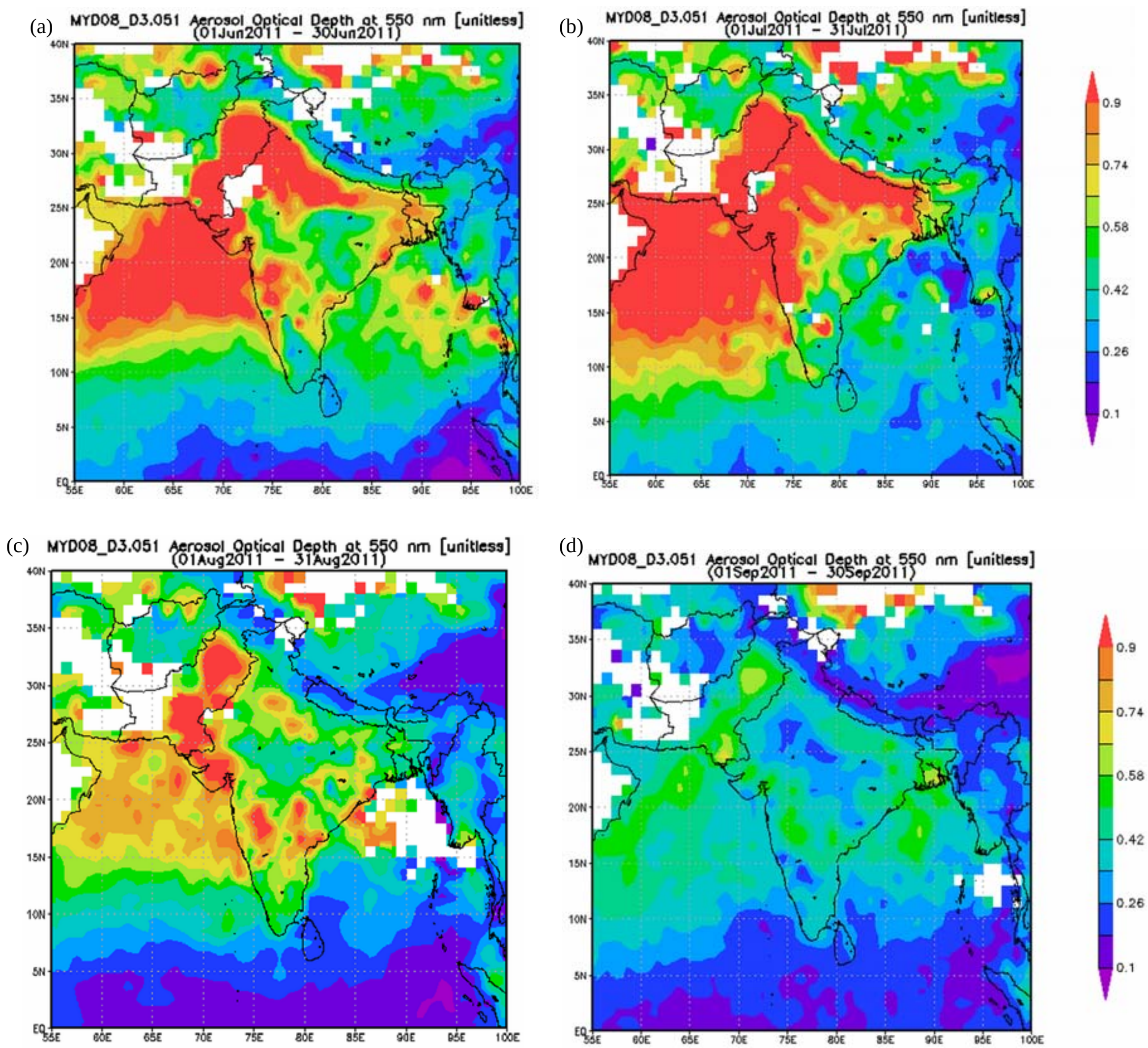


Fig. 6. Weekly IOD Index from 22nd December 2010 to 28th September 2011

could have resulted in resurgence of the monsoon activity witnessed in August and September 2011. Alternatively it cloud be also conjectured whether the organisation of the convection within the monsoon region abort the warming tendency in Nino 3.4 and Nino 3 regions. Similarly, it cloud also lead to change the tendency for a positive IOD mode. The ENSO-Monsoon connection and the IOD-Monsoon connections are very complex and their rapid change within a monsoon season in their relation as witnessed in Monsoon-2011, calls for further reason about the cause and effect of each phenomenon on the monsoon or *vice versa*. Keeping all these aspects into consideration



Figs. 7(a-c). Aerosol Optical Depth (at 500 nm) over (a) Jodhpur (b) Delhi and (c) Varanasi obtained from IMD's Sun-Sky radiometer for the period 1st June to 30th September 2011



Figs. 8(a-d). MODIS (Aqua) aerosol optical depth at 550 nm for the month of (a) June, (b) July, (c) August and (d) September 2011

Monsoon-2011 gives a good example of studying a season with little external influence on the monsoon system. The day to day fluctuations in rainfall happened as a result of entirely internal variability of the monsoon through the activity of monsoon trough.

5. Role of aerosols during monsoon-2011

In developing countries like India, the load of aerosol has considerably increased due to natural and anthropogenic sources which influence the regional climate (Ramanathan and Carmichael 2008; Jayaraman *et al.*, 2001). The population growth accompanied by industrialization leads to vast increase in anthropogenic aerosols whereas natural aerosols originating mainly from the deserts in Rajasthan and adjoining countries of the Arabian Peninsula. Aerosol loading is found to be more over the northern parts than southern parts of India (Singh *et al.*, 2005; Gautam *et al.*, 2009).

The aerosol loading in the IG Plain during Monsoon-2011 remained small for many days as the monsoon trough for most days remained south of the normal position [Figs. 7(a-c) and Figs. 8(a-d). As the monsoon trough remained south of the normal position for season as a whole, marine origin near-surface easterly flow prevailed over the IG Plains as such desert origin dust laden air remained confined to west of 70-75° E.

Aerosol optical depth (AOD) data retrieved from Sun-Skyradiometer installed by IMD at Jodhpur, Delhi and Varanasi are shown in Fig. 7. AOD (at 500 nm) shows gradual increase in June and July and values are varying between 0.5 and 1.5. This was the period when either the

TABLE 1

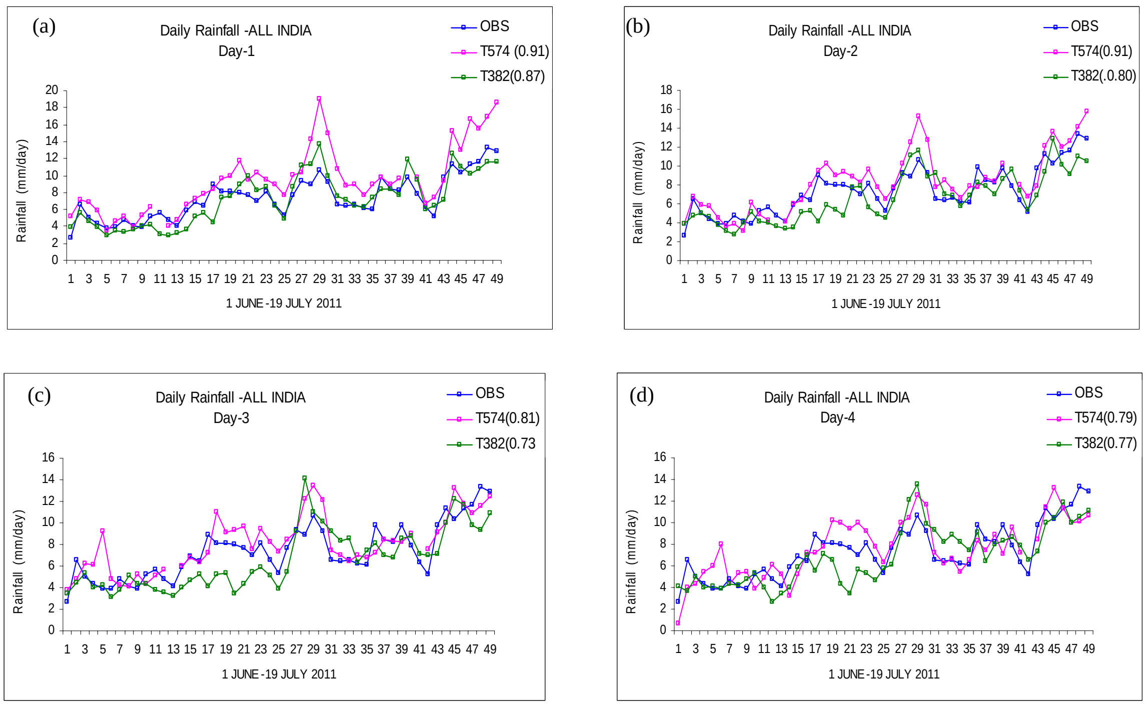
Vector Error (km) of centre of LPSs between model analysis and forecast

	Model	24 hours forecast	48 hours forecast	72 hours forecast
June	ECMWF	91	106	162
	IMD-GFS	120	151	209
	IMD-WRF	119	186	175
July	ECMWF	168	167	273
	IMD-GFS	163	228	257
	IMD-WRF	212	174	193
August	ECMWF	95	111	283
	IMD-GFS	142	268	254
	IMD-WRF	159	215	344
September	ECMWF	109	162	227
	IMD-GFS	102	191	224
	IMD-WRF	154	254	289
Seasonal (2011) (June to September)	ECMWF	116	137	236
	IMD-GFS	132	210	236
	IMD-WRF	161	207	250

monsoon was advancing over Gangetic Plain (June) or was weak (July). From 2nd August onwards to the end of season AOD decreased over these stations as the monsoon became active. Fig. 8 shows the monthly average AOD (at 550 nm) derived from Moderate Resolution Imaging Spectroradiometer (MODIS). AOD values were high along the Gangatic Plains during June and July but sharp decline was observed during August and September as the monsoon trough remained over the region with prevalence of moist maritime air over the Plains. This is a way monsoon activity itself modulated the AOD. If the monsoon is weak (strong) AOD are high (low) over the Gangetic Plain.

6. Performance of NWP models up to 72 hours forecast

Recently IMD has introduced a high resolution GFS models (GFS-T382L64 and GFS-T574L64) for operational weather forecasting. These models were being used in Monsoon-2011. The performance of NWP models has been examined for all the LPSs on the basis of the forecast of the centre of the cyclonic circulation, as depicted in analysis & forecast at 850 hPa level. Forecasts were also examined for 24 to 72 hours based on the ECMWF, IMD-GFS and WRF models. Table 1 shows the performance of the models in track prediction (vector error) for each LPS; average for June, July, August, and September and for the seasonal overall. It is found that the average errors are considerable (160-250 km) and the errors grow with advance in forecast period. The models still need improvement in the track predication as only that would result in improved prediction of high impact rainfall which is centred within about 300 km of southwest sector of LPS in any monsoon season. As already stated IMD's NWP unit at New Delhi was running two high resolution atmospheric general circulation models (GFS-T382L64 and GFS-T574L64) under real-time operations for Monsoon-2011. The performance of the two models for daily rainfall predictions on all-India basis for day-1 to day-4 (24 hours to 96 hours) is shown in Fig. 9 from 1st June to 19th July 2011. It is observed that both the models picked up the variations in the rainfall satisfactorily for day-1 and day-2 forecasts. However, the performance deteriorated by day-4 on several occasions. The fall in rainfall between 24th June to 5th July as well as the rise in rainfall between 10th to 17th July are well picked up by the models even on day-3 and day-4 forecasts. Fig. 10 shows the correlation coefficient between GFS-T382L64 and GFS-T574L64 rainfall forecasts based on 39 days over verification. Up to day-3 GFS-T574L64 forecast showed slightly better skill. Better predictions remained upto day-3 but on day-4 and day-5 the differences in the forecasts of the two models is not significant. If the forecast rainfall is accumulated upto a week (168 hours forecast) the predictions in the two models are very close to each other, but not in good agreement with the observed accumulated rainfall (Fig. 11). We are lead to conclude that the model forecasts can be used as a good guidance up to day-3 but certainly not beyond day-5.



Figs. 9(a-d). Performance of GFS-T382L64 and GFS-T574L64 for daily rainfall predictions on all-India basis of (a) Day-1, (b) Day-2, (c) Day-3 and (d) Day-4

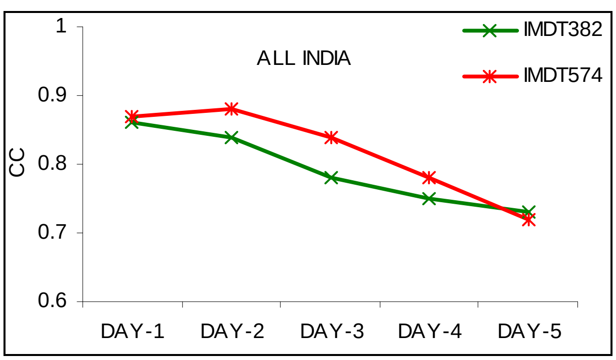


Fig. 10. Compared to GFS-T382L64, GFS-T574L64 has better skill (correlation) in all day 1 - day 4 forecast, indicating the better predictability of daily mean rainfall over India

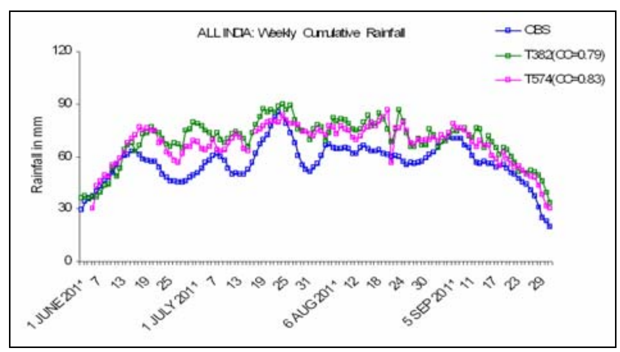


Fig. 11. 168-hour accumulated rainfall forecast by GFS-T382L64 and GFS-T574-L64 over all-India is in phase with observed rainfall, indicating the predictability of rainfall in weekly time scale

7. Comparison of large scale features of monsoon-2011 with monsoon-2010

After the major drought of monsoon-2009, India's seasonal monsoon rainfall has been within the normal but slightly on the positive side for the seasons of 2010 and 2011 (about +2%). Even though in both these seasons India as a whole received about the same quantum of rainfall but the monsoon circulation was quite different in these two years. Some of the important features are highlighted as follows:

(*i*) In both the years the monsoon onset occurred early by 1 day (2010) to 2 days (2011). However, the advance was without any hiatus in 2011 (except for Gujarat State) but a major hiatus had occurred in 2010 between 19^{th} -30^{th} June over Bihar, Uttar Pradesh and north Madhya Pradesh.

(*ii*) Whereas 14 LPSs with no depression occurred in 2010, 14 LPSs with 4 depressions occurred in 2011. However, during the season of 2011 more number of LPSs occurred in an over-lapping manner as the monsoon trough fluctuated in near normal position in August and September 2011.

(*iii*) Both the seasons did not witness any break monsoon spell.

(*iv*) Monsoon withdrawal from NW India was delayed till the 4th week of September in both the seasons. Thus with early advance and late withdrawal the duration of the monsoon was longer than normal over NW India for both the years.

(*v*) La-Nina conditions were fully established in the central Pacific at the beginning of Monsoon-2010 and hence it was expected that the season will end with a positive departure of rainfall from normal on the country scale. However, in 2011, ENSO was in near-neutral condition. By the beginning of the 2011 season, there was warming SST tendency over El Nino 3.4 and hence below normal rain could be expected for monsoon 2011 and was also predicted so by different models except the Indian Institute of Tropical Meteorology (IITM)'s coupled model. However, for the season as a whole ENSO-neutral conditions persisted and the performance of the monsoon was very close to normal.

(*vi*) IOD mode was not very favourable for monsoon 2010 and was opposite to ENSO mode. For monsoon 2011 both the ENSO and the IOD modes remained in neutral conditions. A tendency for these modes to become favourable for monsoon was noted between August and September 2011. Monsoon-2011 performed well merely due to proper oscillations of the monsoon trough in the monsoon zone, chiefly remaining unaffected by the ENSO as well as IOD modes. What made fluctuate monsoon trough in the near normal position during August & September is the major question which needs to be examined by further study of CTCZ data.

8. Concluding remarks

As it happens in a normal monsoon season, the evolution of the Monsoon-2011 had small baffling points which would need research by the CTCZ community. According to our assessment the following research need to be pursued:

(*i*) In spite of adequate soil moisture rise in Gujarat State toward the end of June 2011, there was a hiatus of monsoon onset over Gujarat. This would also need further study. The reason for the regular and quite robust advance may also be a matter of further research.

(*ii*) Except for short period in mid-July, monsoon trough remained generally south of the normal position and transient disturbances continued to form at more or less regular intervals. There was a period toward the middle of July, when there was anxiety about the weak monsoon conditions during July. However, once the monsoon revived in the first week of August, it continued to perform very well till 20th September.

(*iii*) There was no strong remote or local forcing of tropical SST as ENSO and IOD remained near-normal. Rather the tendency toward El-Nino warming and IOD negative mode were reversed in the mid-season during August 2011, for reasons unknown at present. The internal feedbacks to the monsoon were perhaps responsible for fluctuations of monsoon trough not to deviate too much from the core monsoon zone. The intra-seasonal northward propagating mode of the monsoon was rather quiet and the MJO activity also did not affect the monsoon. This aspect is the central point for further investigations to determine the factors over the season which were responsible for restricting the monsoon trough fluctuations to remain within the core monsoon zone. Does it mean that the SST boundary conditions of the extreme ENSO cycle manifestation (positive vs. negative), and IOD are responsible for making the regional monsoon system perform in extreme manner which otherwise would fluctuate within the core monsoon zone. Both data and modelling studies would help in further understanding of monsoon fluctuations.

(*iv*) As indicated by AOD data from Sun-Sky radiometer and MODIS data during Monsoon-2011, desert aerosols were not permitted to enter over India as the marine monsoon easterlies continued to prevail over the IG Plain. Thus, aerosol-monsoon connections are perhaps linked with overall dynamics of the monsoon. If the monsoon is in a prolonged weak/break condition the dusty northwest air stream enters the IG Plain which makes the AOD high. On the other hand prevalence of marine air mass (easterly wind) over IG basin with the monsoon trough lying south of the normal position the possibility of dusty northwest air stream is minimised and hence the aerosol load is reduced. However, it is possible that once the monsoon becoming weak or enters a prolonged break the enhanced aerosol load in the IG Plain may provide a negative feedback to the performance of the monsoon (Sikka, 2010).

(*v*) For understanding the role of cloud processes in a well behaved monsoon season, Monsoon-2011 offers a great opportunity. Similarly, for the study of hydrological processes in monsoon, the first fortnight of September is crucial as the rain over Odisha changed from -17% at the end of August to -3% by 28th September. Odisha region where the CTCZ land surface processes campaign is centred offers opportunities for studying role of hydrological processes during Monsoon-2011 and the data collected would provide important clues. Also, the hydrological feedbacks need to be examined in respect to their role in the formation of LPSs over the IG Plains in Monsoon-2011.

(*vi*) It's also important to focus on the short and medium range predictions of the several depressions and low pressure areas. Initial difference between ECMWF, IMD GFS and WRF models for the centre of the transient were about 100 km offset in several cases. 24 to 72 hour predictions of the centres of disturbances also differed by about 150-250 km of each other. Thus, the uncertainty in the forecast positions of the transients is quite high based on the three models, this has to be reduced. For this goal enhancement of observational data over India offers a possible key. During Monsoon-2011 Indian radiosonde network performed with only 50% operational credibility as due to lack of supplies at the stations soundings were missed. This is within possibility of correction in future years. Initial errors due to lack of radiosonde data have to be minimized as no amount of Automatic Weather Stations (AWS) would help in determining the vertical structure of the atmosphere.

Acknowledgement

The authors acknowledge the support of IMD for the functioning of the CTCZ operational Centre. The authors are thankful to Dr. Sasaki of JMSTEC, Japan for performing weekly IOD Index for preparing Fig. 3. Thanks are also to Dr. S. K. Roy Bhowmik, Head of the IMD's NWP Unit at New Delhi for providing Figs. 6, 7 and 8. Special thanks to Shri V. K. Soni, EMRC, IMD, New Delhi for providing Sun-Sky radiometer data. The authors are also thankful to Dr. Matthew C. Wheeler, Centre for Australian Weather and Climate Research for RMM1, RMM2 space diagram. MODIS analyses and visualizations used were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

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