MAUSAM, **66**, 3 (July 2015), 551-568

551.509.5 : 551.553.21 (540.27)

Rapid northward progress of monsoon over India and associated heavy rainfall over Uttarakhand: A diagnostic study and real time extended range forecast

D. R. PATTANAIK, D. S. PAI* and B. MUKHOPADHYAY*

India Meteorological Department, New Delhi – 110 003, India

**India Meteorological Department, Pune – 411 005, India*

e mail : drpattanaik@gmail.com

सार – वर्ष 2013 में भारत में मॉनसून की असामान्य विशेषता यह रही कि मॉनसून 1 जून को सामान्य रूप से प्रारम्भ होने के बाद दक्षिणी छोर से उत्तर की ओर तेजी से बढ़ा। 16 जून को पूरे भारत में मॉनसून छा गया जिससे सामान्य रूप से उत्तरी भारत के अधिकांश भागों और विशेष रूप से उत्तराखंड मौसम विज्ञान के उपखंड़ों में जून माह में अत्यधिक भारी वर्षा हुई जिसके कारण बहुत अधिक मात्रा में जान और माल की हानि हुई। इस अध्ययन मे मॉनसून के तेजी से बढ़ने के असामान्य आचरण से संबंधित नैदानिक अभिलक्षणों का विश्लेषण किया गया है। युग्मित मॉडल आऊटपुट पर आधारित वास्तविक समय विस्तारित दूरी के पूर्वानुमानों के निष्पादन का भी विश्लेषण किया गया। इसके लिए 16 सदस्यों वाली NCEP (जलवायु पूर्वानुमान प्रणाली वर्जन 2), CFSv2 नवीनतम युग्मित मॉडल, 50 सदस्यों वाली जापान मौसम विज्ञान ऐजेंसी (JMA) और समुच्चय प्रागुक्ति प्रणाली के पूर्वानुमानों का उपयोग किया गया है।

उत्तरी भारत तथा विशेषकर उत्तराखंड में अभूतपूर्व वर्षा सहित उत्तर की ओर तेजी से बढ़ता मॉनसून निम्न अवदाब वाले क्षेत्र से संबंद्ध था जिसके कारण उत्तरी भारत के आर्द्रता अभिसरण में वृद्धि हुई और यह उपरितन स्तर के गहन पश्चिमी द्रोणी से संबद्ध था। दोनों मॉडलों द्वारा उत्तर पश्चिमी भारत में भारी वर्षा से संबद्ध तथा उत्तर पश्चिमी भारत में मॉनसून के तेजी से बढ़ने की प्रक्रिया बताई गई और पूरे भारत में मॉनसून के छा जाने से संबंधित पूर्वानुमान के लम्बी अग्रणी समय के साथ JMA सहित MME मॉडल का निष्पादन थोड़ा बेहतर रहा। उत्तराखंड में वर्षा के अत्यधिक मात्रा में वापस जाने में CFSv2 मॉडल की अपेक्षा JMA मॉडल का निष्पादन बेहतर रहा, तथापि यह प्रेक्षण की अपेक्षा कम आकलित भी किया गया और यह निम्न स्तर अभिसरण सहित उपरितन स्तर के पश्चिमी द्रोणी की परस्पर क्रिया को मॉडल द्वारा न अपनाए जाने के कारण भी हो सकता है। तथापि विस्तारित दूरी में मॉनसून पूर्वानुमान की उपयोगी कौशल अखिल भारतीय स्तर के साथ-साथ उत्तर पश्चिमी भारत के छोटे से छोटे क्षेत्र में भी पाया गया।

ABSTRACT. The unusual features of monsoon over India during 2013 was it's rapid progress northward from southern tip of India after normal onset on 1st June. The monsoon covered entire India by 16 June and it witnessed very heavy rainfall in June over many parts of northern India in general and Uttarakhand meteorological subdivision in particular, leading to large scale destruction of life and property. In the present study the diagnostic features associated with this unusual behaviour of rapid progress of monsoon is analysed. The performance of the real-time extended range forecasts based on coupled model outputs is also analysed. The latest coupled model from NCEP (the climate forecast system version 2; CFSv2) with 16 members, Japan Meteorological Agency (JMA) Ensemble Prediction System (EPS) with 50 ensemble members and Multi-model ensemble (MME) forecasts are used for this purpose.

The rapid progress of monsoon northward with unprecedented rainfall over north India and particularly over Uttarakhand was associated with the movement of low pressure area leading to the increase in moisture convergence over northern India and juxtaposition with upper level deep westerly trough. The rapid progress of monsoon to Northwest India and associated heavy rainfall over northwest India are captured by both models and MME with JMA model performed slightly better in terms of longer lead time of forecasting the coverage of monsoon to entire India. The JMA model performed better in terms of higher departure of rainfall over Uttarakhand compared to that in CFSv2 model, although, it was also underestimated compared to observation and it could be due to the fact that the interaction of upper level westerly trough with the low level convergence was not captured in the model. However, useful skill of monsoon forecast in the extended range is observed on all India level and also over the smaller domain of northwest India.

Key words – India monsoon onset, Multi-model ensemble, Westerly trough, Heavy rainfall, Coupled model, Extended range forecast.

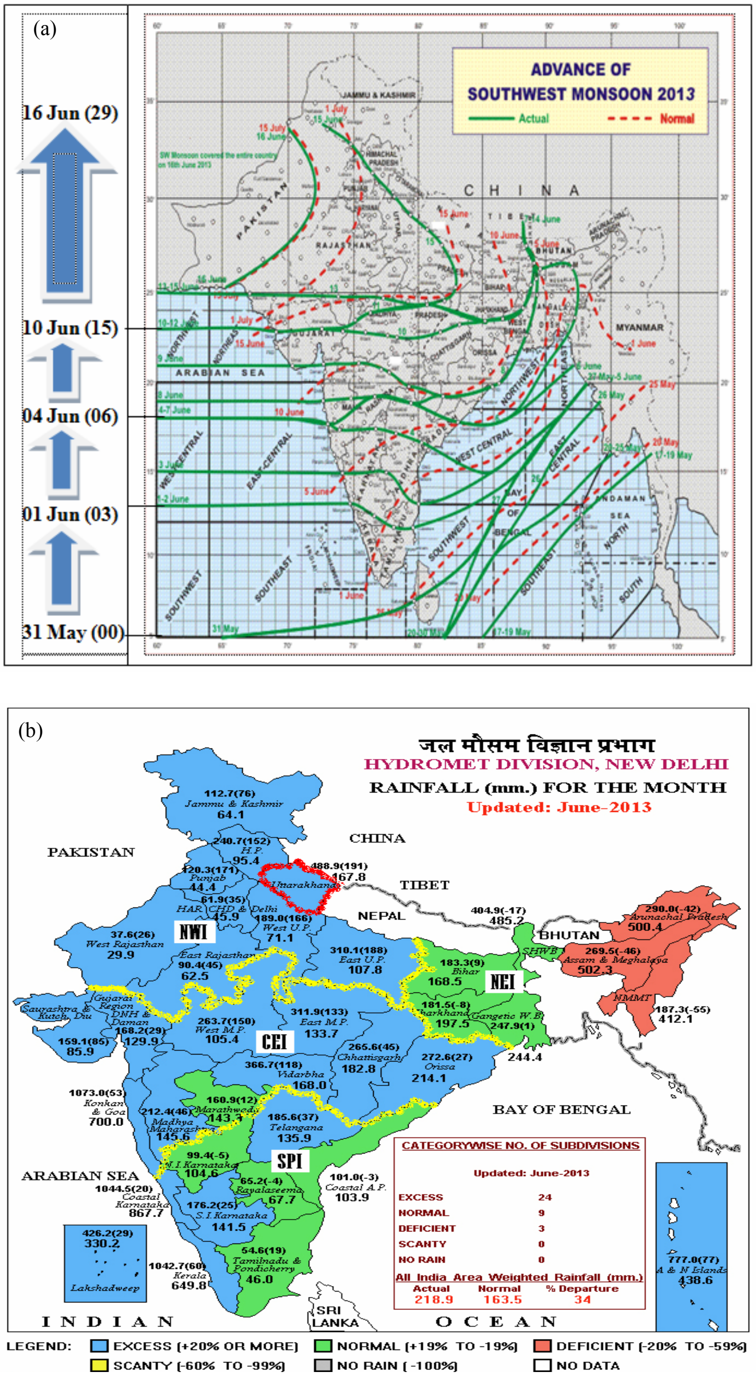
1. Introduction

The monsoon flow represents much more than a giant sea breeze circulation. The evolution, advancement (rapid progress or stagnation aspects) and retreat are the most important epochs associated with the summer monsoon over India, as they essentially decide the effective duration of the summer monsoon and the quantity of rainfall over different parts of the country. The arrival of the summer monsoon over India is also of great importance, occurring towards the end of May or in early June over the southern tip of the Indian (Kerala) coast. The evolution of the monsoon onset processes is characterized by intensification of low-level circulation, particularly the cross-equatorial flow off the East Africa coast, in response to the heating over the Arabian Peninsula, Pakistan and northwest India and formation of heat low over northwest India. It is well recognized that the onset of the summer monsoon is accompanied by distinct changes in the large-scale circulation and rainfall distribution over the Indian landmass and surrounding oceanic regions. These include the northward displacement of upper tropospheric westerly flow to the north of the Himalayas, establishment of the upper level tropical easterly jet (TEJ) stream (Koteswaram, 1958) and lower tropospheric westerly jet (Somali jet) over the Arabian Sea (Findlater, 1969). Study by Raju *et al*. (2005) also found that the strength of the low-level Somali jet and upper tropospheric tropical easterly jet increase rapidly during the time of evolution of the summer monsoon over India. The intensification of the monsoon flow is mainly dictated by the release of convective instability and tropospheric diabatic heating (Krishnamurti and Ramanathan, 1982; Mohanty *et al*., 1983; Pearce and Mohanty, 1984; Rao and Aksakal, 1994). Studies by Ananthakrishnan and Soman (1988, 1989) and Soman and Krishnakumar (1993) documented the climatological structure of the meteorological fields associated with the onset phase of the summer monsoon. Fasullo and Webster (2003) have also shown that the variability of rainfall at Kerala during the onset phase results from both local synoptic variability and large-scale dynamics of the summer monsoon, and their relationship is not very well known.

Although, there was no precise definition of the onset of the monsoon initially, in conventional manner, meteorologists in India identify the date of onset over the Kerala coast based on a sharp increase and characteristic persistency of the rainfall (Ananthakrishnan *et al*., 1968). Presently, India Meteorological Department (IMD) is using three objective criteria (available in http://www.imd.gov.in/monsoon.htm) to declare the official start of the summer monsoon, *viz*., (*i*) if, after May 10, 60% of the available 14 stations in the state of Kerala (The state “Kerala” is identified in Fig. 1) report rainfall of 2.5 millimeters (roughly 0.1 inches) or more on two consecutive days, then the IMD declares the onset over Kerala on the second day, provided following two conditions are also met. (*ii*) The depth of the westerlies must be maintained up to 600 hPa (roughly 4.5 kilometers above the ground) in the box bounded by the region Eq - 10° N and 55° E - 80° E with the zonal wind speed over the area bounded by this region must be of the order of 15 to 20 knots at 925 hPa and (*iii*) Satellite-derived values of Outgoing Long-wave Radiation (OLR) must be less than 200 watts/m^2 in the box bounded by 5° - 10° N and 70° - 75° E.

The southwest monsoon normally sets in over Kerala around 1st June. It advances northwards, usually in surges, and covers the entire country around 15 July. The northern limit of monsoon (NLM) is the northern most limit of monsoon upto which it has advanced on any given day. One of the unusual features of monsoon 2013 is the rapid progress of monsoon from southern tip of India as a result the NLM moved northward very fast and the monsoon covered entire India by 16 June [Fig. 1(a)]. The pace of advance of southwest monsoon in 2013 had been the fastest during the period 1941-2013 as it took only 15 days to cover the entire country after its normal onset on 1st June. Associated with this rapid progress of monsoon northward there was also very unusual heavy rainfall over Northwest (NW) India particularly over the meteorological sub-division of Uttarakhand during this onset phase as seen from the sub-division wide monthly rainfall departure during June, 2013 [Fig. 1(b)] with all the meteorological subdivisions over NW India indicating excess rainfall (a departure ≥20%) with the meteorological subdivision of Uttarakhand reported a departure of 191% marked in Fig. 1(b). This particular case of rapid advance of monsoon with vigorous rainfall activity is associated with movement of a monsoon low from NW Bay of Bengal across central India to NW India during this period (Devi and Yadav, 2014).

In addition to the importance of the forecasting of seasonal total rainfall over India in a particular year, the extended range forecasting of the onset and the sub-seasonal variability (active/weak periods) are of significant relevance for the Indian economy. A late or early onset of the monsoon and break periods in the monsoon rainfall may have devastating effects on agriculture, even if the mean rainfall in the monsoon season as a whole is normal. In last few decades, many statistical and dynamical models have been developed for predicting the summer monsoon rainfall both in the extended range and the seasonal scale. Atmospheric General Circulation Models (AGCM) and Coupled GCMs (CGCMs) are the main tools for dynamical seasonal scale prediction. Some of the recent studies have highlighted that the coupled models with one-tier approach can enhance the predictability of the summer monsoon precipitation (Pattanaik & Kumar, 2010; Krishnan *et al*., 2011). One of the dominants factors, which, influences the Intra-seasonal oscillation of monsoon is the Madden Julian Oscillation (MJO). The MJO is the leading mode of tropical intra-seasonal climate



Figs. 1(a&b) (a) Onset and progress of monsoon over India during 2013. (b) Met-sub-division wise rainfall during June with circle in red indicated the meteorological sub-division of Uttarakhand. The four homogeneous regions (NWI : northwest India; NEI : northeast India; CEI : central India; SPI : south-peninsular India)

variability and is characterized by organization on a global spatial scale with a period typically ranging from 30-60 days (Madden and Julian, 1971 & 1994; Zhang 2005). Thus, the capability of statistical or numerical models in capturing MJO signal is very crucial in capturing the intra-seasonal cycle of monsoon. Now the growing demand for the country like India is to have a better forecast of monsoon on extended range time scale. Many recent studies have shown encouraging results about the forecasting of monsoon on extended range time scale using coupled models and multi-model ensembles (Pattanaik, 2014; Pattanaik *et al*., 2013; Abhilash *et al*, 2014). The objective of the present study is to first make the diagnostic study pertaining to the rapid progress of monsoon northward and associated heavy rainfall over NW India during 2013. Secondly, the extended range forecast of this unusual feature of monsoon during the onset phase of 2013 was also investigated using coupled models outputs and its multi-model ensembles.

2. Data and methodology

2.1. *Observed data used in the present study*

For the study of observational features of the rapid progress of monsoon during 2013, the data from NCEP/NCAR reanalyses (Kalnay *et al*., 1996) has been used. The daily OLR data used during the season is from the Advanced Very High Resolution Radiometer (AVHRR) instrument obtained from NOAA (Gruber and Krueger, 1984). The rainfall observations from large number of stations spread over the entire Indian land mass are used by IMD to prepare the daily time series of area averaged monsoon rainfall over Indian as a whole and also over the smaller spatial regions. This observed data set of rainfall obtained from IMD over all India, NW India and 36 meteorological sub-divisions over India demarcated in Fig. 1(b) are used for the verification purpose. For the spatial distribution of rainfall over the surrounding oceanic region outside India, the observed rainfall available from Tropical Rainfall Measuring Mission (TRMM) is also used for the purpose.

2.2. *Models outputs used for real time extended range forecast*

Outputs from two well known models are used for the extended range forecast of onset phase of monsoon during 2013. The National Centre for Environmental Prediction's (NCEP's) Climate Forecast System version 2 (CFSv2) and the JMA's ensemble prediction system (EPS) are used in the present study. The details of these models forecasts and the methodology of multi-model ensembles (MME) are given here.

2.2.1. *NCEP's climate forecast system (Version 2)*

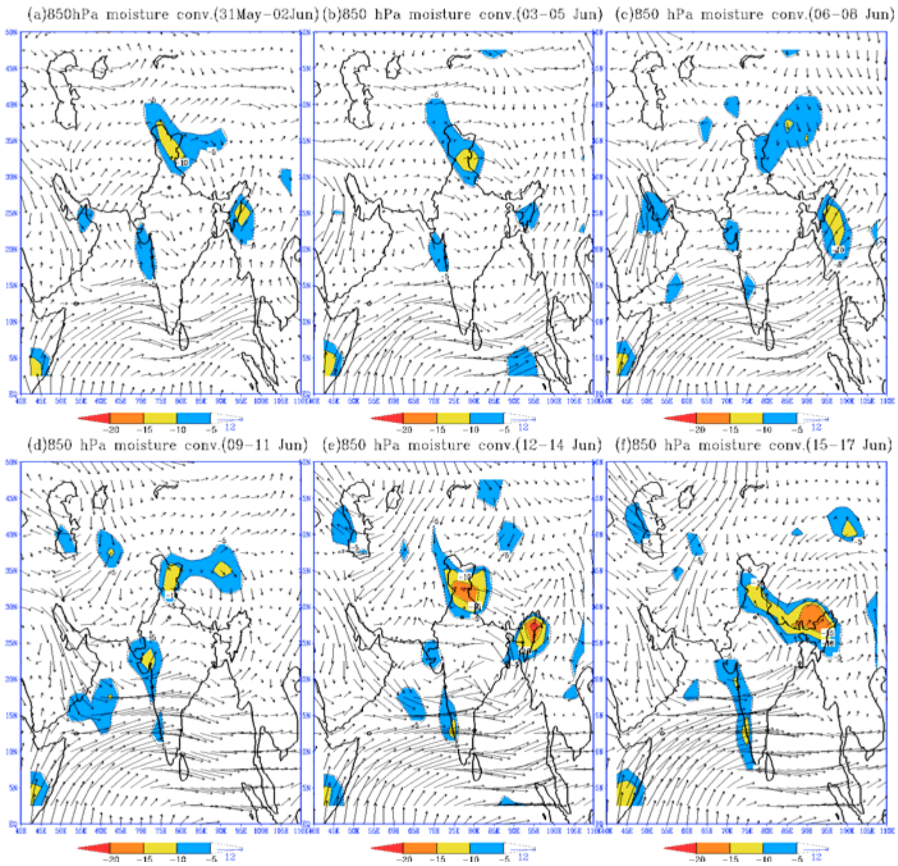
The Climate Prediction Centre, NCEP was running operationally the coupled model known as the Climate Forecast System version 1 (CFSv1) from 2004 (Saha *et al*., 2006). The atmospheric component of the operational CFSv1 (T62L64/MOM3) is the NCEP atmospheric GFS model. The oceanic component is the GFDL Modular Ocean Model V.3. The CFSv1 is a fully 'tier-1' forecast system. The second version of the NCEP Climate Forecast System (CFSv2) was made operational at NCEP in March, 2011. This version has upgrades to nearly all aspects of the data assimilation and forecast model components of the system. The atmospheric model has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. In operational mode the CFSv2 runs with 16 members daily (Saha *et al*., 2014). The CFSv2 run based on every Thursday and valid for the forecast periods of days 5-11 (here after called week-1), days 12-18 (here after called week-2), and days 19-25 (here after called week-3), coinciding with Monday-Sunday and for the subsequent Mondays-Sundays are used.

2.2.2. *Ensemble prediction system (EPS) from JMA*

The outputs from other numerical prediction model (V1103) used here is the Ensemble Prediction System (EPS) of Japan Meteorological Agency (JMA). The details of the EPS system used can be available from (http://ds.data.jma.go.jp/tcc/tcc/news/tccnews35.pdf). The atmospheric general circulation model (AGCM) is a low-resolution version (TL159) of the Global Spectral Model (GSM) used for short- and medium-range forecasting at an approximate horizontal resolution of 110 km with 60 levels in the vertical with top most layers at 0.1 hPa. Persisted SST (COBE SST; Ishii *et al*., 2005) anomalies and climatology of Sea ice analysis (at 1.0° × 1.0° resolution) is used. The model is run with 50 ensemble members on every Thursday and the ensemble members are generated using the combination of Breeding of Growing Modes (BGM) and Lagged Average Forecast (LAF). The JMA EPS model also generates forecast for 32 days based on every Thursday.

2.2.3. *Multi-model ensemble (MME) forecast*

The hindcast mean is calculated from NCEP CFSv2 (23 years climatology) and JMA (25 years climatology). Based on the respective hindcasts climatology of both models the weekly anomaly field is calculated from CFSv2 and JMA model with forecast period valid for days 5-11 (week-1), days 12-18 (week-2) and days 19-25 (week-3). The anomalies fields are converted into uniform latitude-longitude grid (0.5° × 0.5°) and the MME is prepared with giving equal weights to both the models. The MME forecast is generated on every Friday with forecast anomaly for week-1 (Monday to Sunday) to week-3 (subsequent Monday to Sunday).



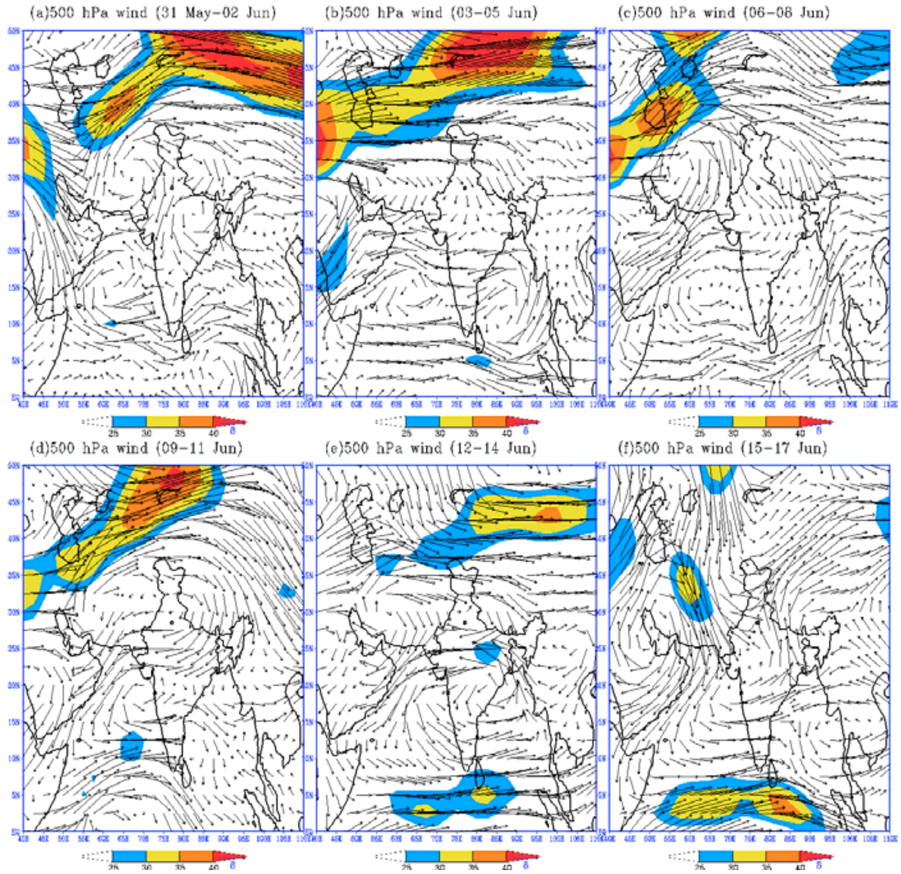
Figs. 2(a-f). 850 hPa 3 days mean wind during onset phase from 31 May to 17 June, 2013 with moisture convergence (10^{-5} gm kg^{-1} s^{-1}) is plotted with shaded

3. Observational characteristics of rapid progress of monsoon 2013

3.1. *Lower, middle and upper tropospheric flow*

As discussed earlier, in addition to the rainfall criteria used by IMD for the objective definition of monsoon onset over Kerala the second criterion used for defining monsoon onset over Kerala is associated with strengthening of the Low-Level Somali Jet (LLSJ), which is a channel of low-altitude, speedy winds that forms off the coast of Somalia and gets drawn eastward toward India by an onset vortex. During the warm season, the LLSJ, with speeds sometimes exceeding 40 knots at 925 hPa (roughly one kilometer up), develops in the month of May as southeasterly trade winds over the Southern Indian Ocean cross the equator and head northward along the east coast of Africa. This low level monsoon flow contributes to the transport of water vapour to Indian region (Pisharoty, 1965).

In order to see the strengthening of wind the three days mean (known as "triad") wind during the period from 31 May to 17 June, 2013 is shown in Figs. 2(a-f). The corresponding moisture convergence at 850 hPa level during the same period in Figs. 2(a-f) indicated by shading information is superposed along with the wind circulation. The corresponding three days mean winds at middle (500 hPa) and upper (200 hPa) tropospheric levels during the period from 31 May - 17 June, 2013 is also shown in Figs. 3(a-f) and Figs. 4(a-f) respectively. During the first triad from 31 May-2 June the onset of monsoon over Kerala coast is associated with southwesterly wind in the Arabian Sea entering to the Bay of Bengal (BoB), becoming southerly/southeasterly near the head BoB and the adjoining land region of India [Fig. 2(a)]. The low level southwesterly/westerly wind gradually penetrated northward with a cyclonic circulation during the triad 3-5 June [Fig. 2(b)] over the BoB. The southwesterly/westerly wind further moved northward along with northward movement of east-west shear line, which is seen along around 20° N during the triad from 12-14 June [Fig. 2(e)] and along around 23° N during the triad from 15-17 June [Fig. 2(f)]. The northward movement of monsoon was facilitated by northwesterly track of the low pressure area formed in the BoB on 12th June and moved inland upto



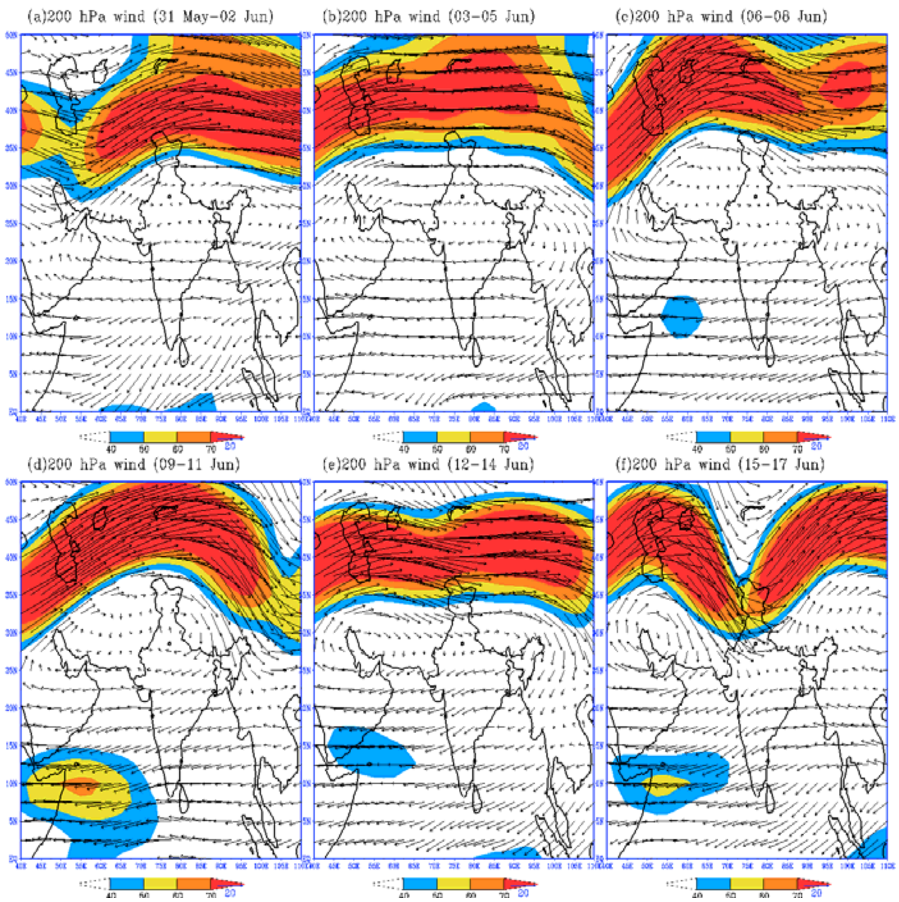
Figs. 3(a-f). 500 hPa 3 days mean wind during onset phase from 31 May to 17 June, 2013

the western state of Rajasthan during subsequent five days (Pai and Bhan, 2014). The middle troposphere wind indicates cyclonic vortices associated with the east-west shear line gradually moving northward along with the advances of monsoon northward [Figs. 3(a-f)].

At upper troposphere the onset of southwest monsoon over Indian subcontinent is driven by the shift of the subtropical westerly jet northwards from over the plains of India towards the Tibetan Plateau (Rao, 1976; Allaby, 2002). This shift of the westerly jet to the north of the Himalayas is not a slow and gradual process, as expected for most changes in weather pattern. As such, the shift of the jet is sudden and abrupt causing the bursting of southwest monsoon rains onto the Indian plains. During 2013 the upper troposphere mean wind for 6 triads from 31 May to 17 June indicates northward shift of westerly jet stream during first 4 triads from 31 May to 11 June [Figs. 4(a-d)]. The sudden change in the upper tropospheric flow was noticed with building up for a deep trough during the triad from 12-14 June with slight southward penetration of westerly jet [Fig. 4(e)] and subsequently penetration of deep trough into Indian region upto about 27° N along the longitude of around 75°E during the triad from 15-17 June, 2013 [Fig. 4(f)]. Such deep trough at upper troposphere can provide additional convergence at lower level ahead of the trough.

3.2. *Lower tropospheric moisture convergence*

With the arrival of monsoon the low-level wind speed over the Indian Ocean increases leading to increase in low level moisture flux. Consequently, the moisture content of the air increases and reaches a level sufficient to produce deep cumulus convection and latent heat release. This provides an additional heat source and the whole circulation continues to intensify through positive moisture feedback, leading to the onset of the monsoon over the Indian subcontinent, which is characterized by deep convection over the Arabian Sea, extending in to the Bay of Bengal and across peninsular India. To see the role of moisture convergence during the rapid progress of monsoon it is superposed with the low level (850 hPa) mean wind shown in Figs. 2(a-f). As shown in Figs. 2(a-f) there was moisture convergence in the northern parts of India from the onset period [Fig. 2(a)] and it continued for



Figs. 4(a-f). 200 hPa 3 days mean wind during onset phase from 31 May to 17 June, 2013

subsequent periods also [Fig. 2(b-f)]. As seen from Figs. 2(a-f) there is sudden increase in the moisture convergence over the northern parts of India from the value of about 5-10×10^{-5} gm $kg^{-1}s^{-1}$ to 14-20 × 10^{-5} gm $kg^{-1}s^{-1}$ during the periods from 12-14 June [Fig. 2(e)], which is further increased during the period from 15-17 June and shifted slightly eastward [Fig. 2(f)]. The increase in moisture convergence during this period is due to the interaction of low level convergence associated with the movement of low pressure area and in conjunction with upper level deep westerly trough shown in Fig. 4(f).

3.3. *Northward propagation of MJO*

The third criteria used by IMD for declaring onset of monsoon over Kerala in addition to the conditions of rainfall and depth of westerly is associated with convection over the Arabian Sea, which say the OLR must be less than 200 watts per/m^2 in the box bounded by box 5° N - 10° N and 70° E - 75° E. The OLR values were between 160 to 200 watts/m^2 during the period from 23rd May to 1st June, 2013 and therefore, was satisfying the onset criteria on 1st June (Devi and Yadav, 2014). Associated with the movement of this convection zone northward the monsoon also progresses northward. Many earlier studies (Sikka and Gadgil, 1980; Krishnamurti and Subramanian, 1982; Pattanaik, 2003) have shown how the northward moving MJO over the Indian longitude contributed in moving the monsoon northward. In order to see the migration of convection belt the daily OLR anomalies averaged between 65° N-85° N from 1st May to 30 June is shown in Fig. 5. As it is seen from Fig. 5 there is a very rapid progress of convection belt over India as indicated by negative OLR anomalies during the period from 5th June to about 18th June, 2013. Thus, the convectively active phase of the MJO and the associated systematic northward propagation of the east-west shear zone at the mid-tropospheric levels contributed to rapid progress of monsoon.

3.4. *Heavy rainfall during the rapid northward progress*

The year 2013 witnessed rapid advance of monsoon over India. Convectively active phase of the MJO and the associated systematic northward propagation of the

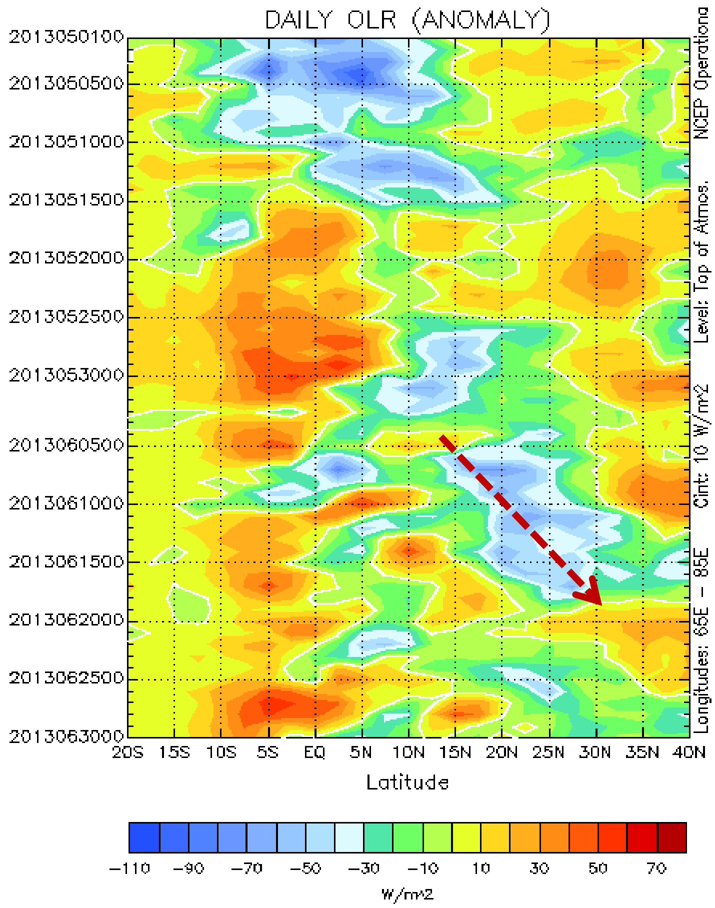
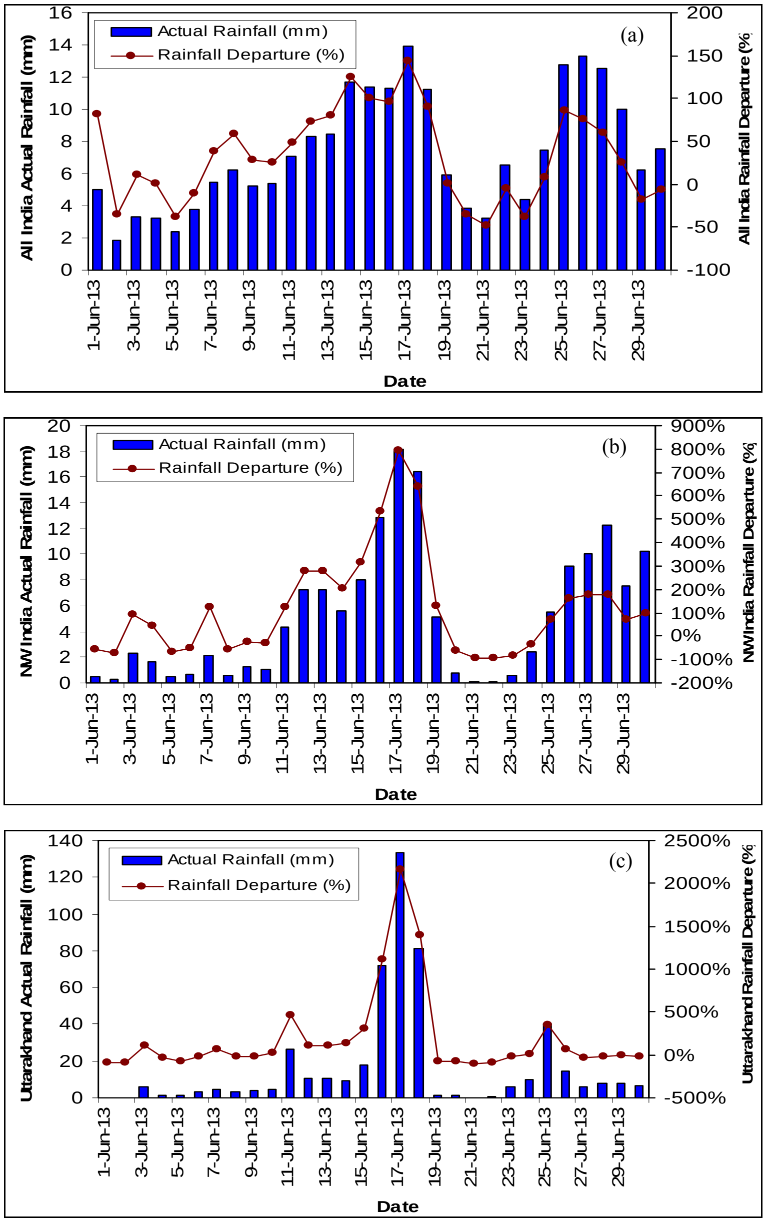


Fig. 5. Daily OLR anomaly averaged over the longitude 65° E - 85° E during 1st May to 30 June, 2013

east-west shear zone at the mid-tropospheric level contributed positively to the rainfall during the onset and advance phase of southwest monsoon over India. Juxta-positioning of a monsoon low pressure system moving from the northwest BoB across central India and its interaction with a deep westerly trough in the upper troposphere contributed to additional moisture convergence in the lower level leading to extremely heavy rainfall events over the western Himalayan region causing death and damage to property. There have been some earlier occasions when the northern India and Pakistan witnessed unprecedented rainfall during peak monsoon period of July and August due to the interaction of lower level monsoon flow and upper level westerly. The unprecedented flood over Pakistan during July-August 2010 was one such event (Hauze *et al*., 2011; Webster *et al*., 2011; Pattanaik *et al*., 2013; WMO 2013). Pattanaik *et al*. (2013) have shown that the rainfall during the period from 26 July to 1 August, 2010 was caused by a very active monsoon trough extending from northern part of BoB to south Pakistan embedded in a cyclonic circulation over north Pakistan region. Hauze *et al*. (2011) have also shown that the rainfall producing the Pakistan floods occurred in storms that were of a type commonly seen far to the east over the Bengal region but rarely over Pakistan and they have further shown that the low pressure area over the northwest and adjoining west central BoB during 28 July to 1 August provided the moist environment across the subcontinent to the Arabian Sea.

The unprecedented rainfall over parts of India during the onset phase of 2013 monsoon can be seen from the daily rainfall averaged over India as a whole, Northwest India and over the meteorological subdivision of Uttarakhand. The daily area averaged rainfall over these three regions along with its departure from normal during 1 June to 30 June, 2013 is shown in Figs. 6(a-c) respectively. As seen from Fig. 6(a) most of the days in June 2013 witnessed above normal rainfall for the country as a whole with relatively higher positive rainfall departure between 100% to 150% during the period from 14-18 June, 2013. This is basically due to the contribution of heavy rainfall over Northwest India during the period

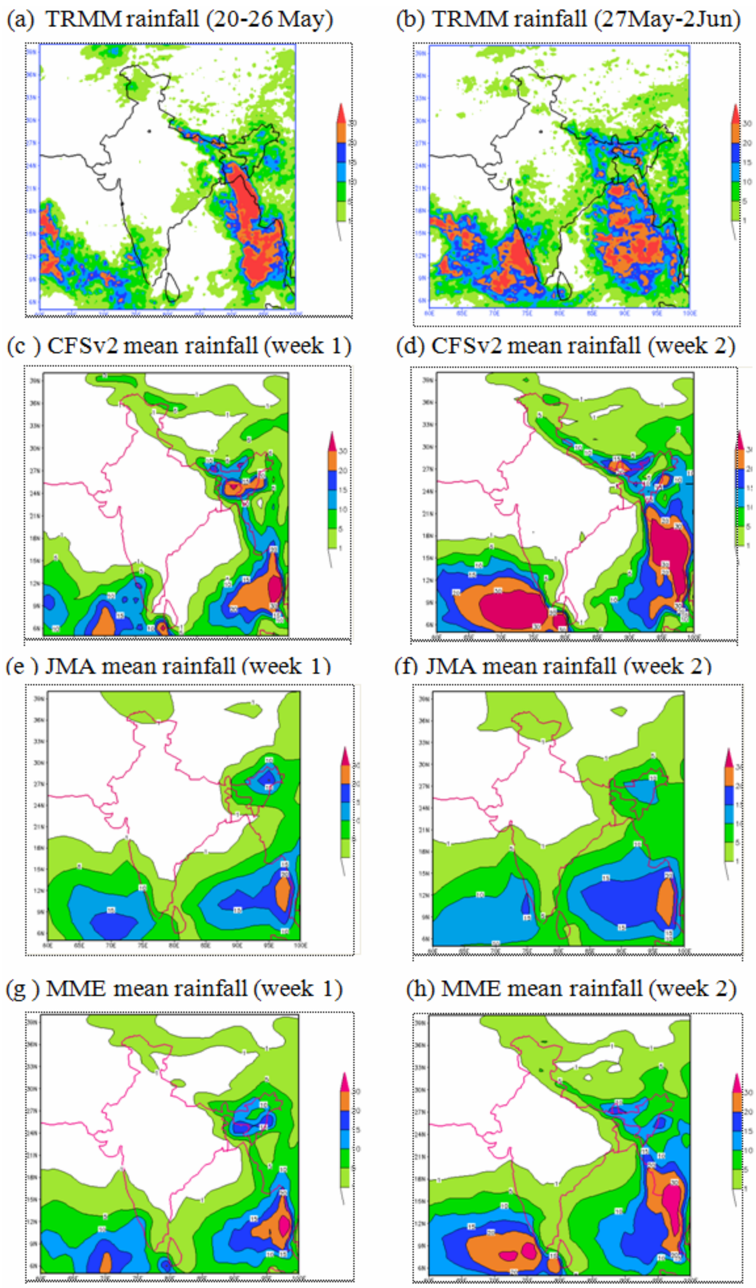


Figs. 6(a-c). Actual daily rainfall (mm) and departure (%) from normal during June, 2013 over (a) All India, (b) Northwest India and (c) Uttarakhanad met sub-division

from 16-18 June with the departure touching a value of about 800% on 17th June, 2013 [Fig. 6(b)]. The most affected meteorological sub-division of Uttarakhand witnessed unprecedented rainfall during that period as shown in Fig. 6(c) with peak intensity of rainfall during the period from 16-18 June, 2013 with a departure of exceeding 2000% on 17th June, 2013. Again on station level some stations in the meteorological subdivision of Uttarakhand received much higher rainfall on few days compared to that is shown in Fig. 6(c) averaged over the whole meteorological sub-division. Thus, the onset phase of monsoon over Northwest India during 2013 was unique and its rapid progress associated with interaction between a monsoon low and mid-latitude trough has caused unprecedentedly vigorous rainfall, resulting in calamitous floods over Uttarakhand.

4. Real time forecasting of onset and rapid progress of monsoon

Now the growing demand for the country like India is to have a better forecast of monsoon on extended range

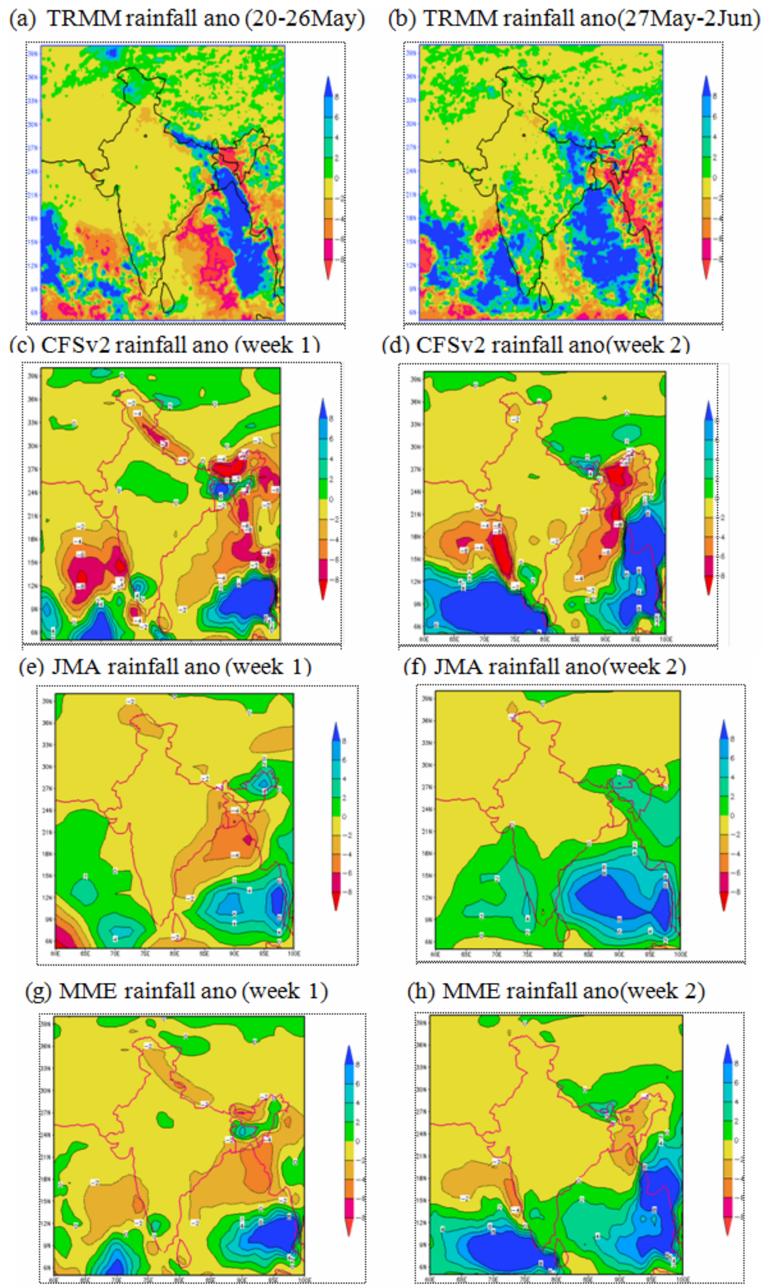


Figs. 7(a-h). Observed (TRMM) and forecasts mean rainfall (mm/day) from CFSv2, JMA, and MME based on 16 May, 2013 and valid for week-1 (20-26 May) and week-2 (27 May-2 June)

time scale. The performance of extended range forecasting of monsoon onset and its rapid progress northward leading to heavy rainfall over Northwest India during 2013 is discussed below.

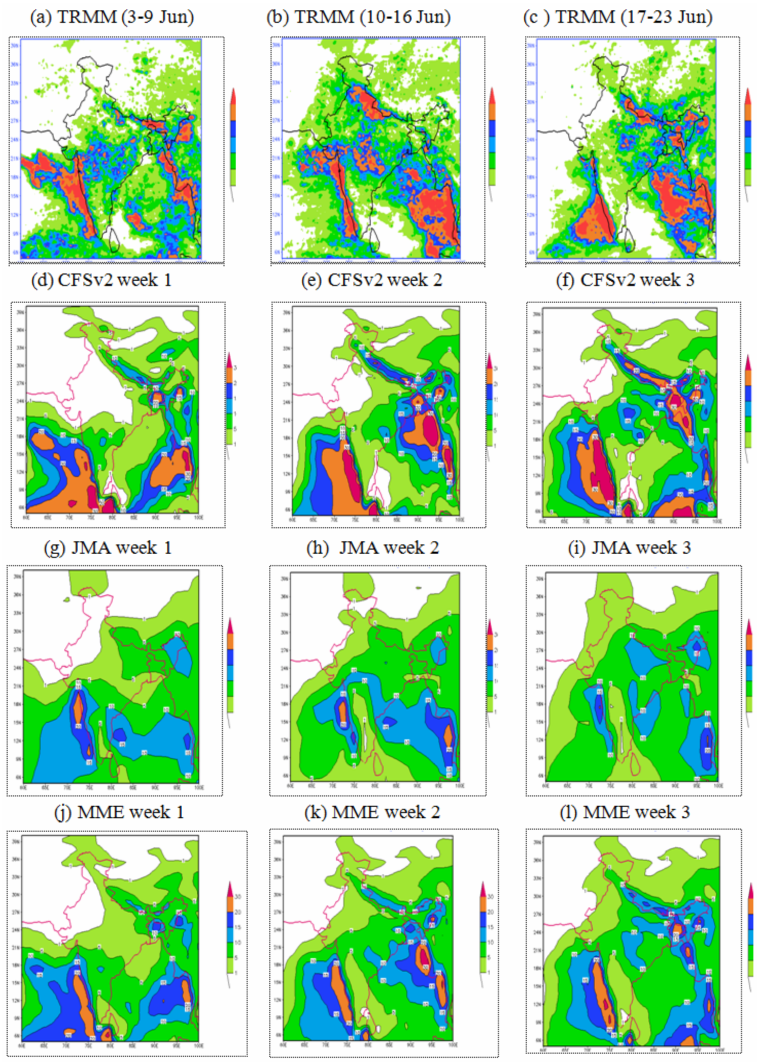
4.1. *Extended range forecast of onset of monsoon*

As per the objective criteria used by IMD the onset of monsoon occurred over the Kerala coast on 1st June, 2013 when the rainfall and other criteria were satisfied. The observed weekly mean rainfall and corresponding rainfall anomalies obtained from TRMM during 20 - 26 May and 27 May - 2 June is shown in Figs. 7(a-b) and Figs. 8(a-b) respectively. The weekly observed rainfall from 20-26 May, 2013 [Fig. 7(a)] shows rainfall activity over southern parts of Arabian Sea close to the Kerala coast. That means the rainfall had already commenced during this period. However, the onset over Kerala coast was



Figs. 8(a-h). Observed (TRMM) and forecasts rainfall anomaly (mm/day) from CFSv2, JMA, and MME based on 16 May, 2013 and valid for week-1 (20-26 May) and week-2 (27 May-2 June)

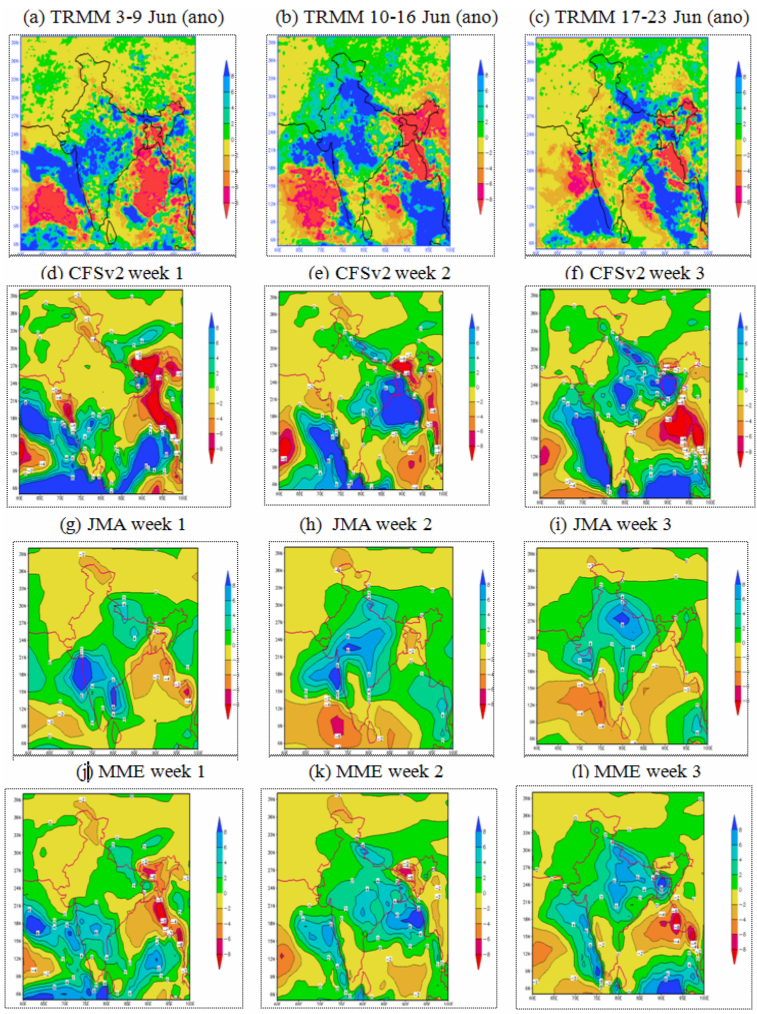
declared on 1st June when the other two criteria are also satisfied (Devi and Yadav, 2014). The observed rainfall during the subsequent week from 27 May - 2 June, 2013 shows increase in rainfall over the west coast and eastern parts of India associated with northward migration of rainfall belt from south and westward migration of rainfall belt from east [Fig. 7(b)]. The observed rainfall anomaly during the week from 20-26 May, 2013 shown in Fig. 8(a) also indicated the positive anomaly belt of rainfall over the south-western coast of India and eastern India prior to the onset. During the subsequent week (onset week) from 27 May to 2 June the positive anomaly rainfall belt from south-western coast moved further northward and the rainfall belt over eastern region moved westward. In order to see the performance of extended range forecast of monsoon onset the forecast weekly mean rainfall from CFSv2, JMA and MME models based on the initial condition of 16th May and valid for week-1 and week -2



Figs. 9(a-l). Observed (TRMM) and forecasts rainfall (mm/day) from CFSv2, JMA and MME based on 30 May, 2013 and valid for week-1 (3-9 June), week-2 (10-16 June) and week 3 (17-23 June)

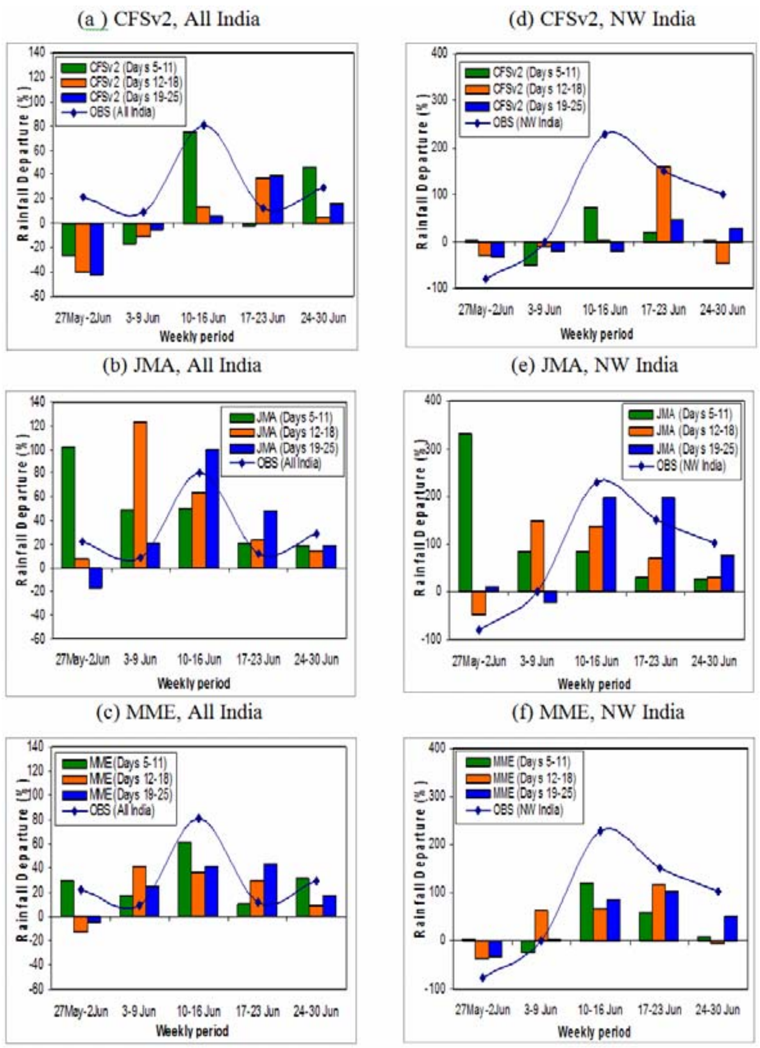
forecasts coinciding with 20-26 May and 27 May - 2 June, 2013 is shown in Figs. 7(c-d), Fig. 7(e-f) and Figs. 7(g-h) respectively. The corresponding forecast rainfall anomaly from individual models and MME valid for 20-26 May and 27 May-2 June, 2013 is shown in Figs. 8(c-d), Fig. 8(e-f) and Figs. 8(g-h) respectively.

Based on the initial condition of 16^{th} May the week-1 and week-2 forecasts mean rainfall [Fig. 7(c-f)] from JMA model indicates the timely onset of monsoon over Kerala during the week from 27 May to 2 June and the CFSv2 model indicating tendency of slight early onset (although, very weak onset) of monsoon during the week from 20-26 May, 2013 as the rainfall belt over southern tip of India reported during the week [Fig. 7(c)] with a small pocket of positive anomaly observed over the region [Fig. 8(c)]. Though, the JMA model also recorded rainfall over southern tip of India during the week from 20-26 May [Fig. 7(e)], the anomaly indicates mainly negative over the southern tip of India during the week [Figs. 8(e)]. However, with respect to the week-2 forecast the progress of monsoon northward and westward during the subsequent week from 27 May - 2 June, 2013 seen in the observed rainfall in Fig. 7(b) is very well captured in the JMA model [Fig. 7(f)]. In the CFSv2 model the week-2 forecast valid for the period from 27 May - 2 June indicates rainfall belt mainly over the southern parts of west coast and adjoining peninsula India and its northward progress is very much restricted [Fig. 7(d)]. The same is also reflected when the observed rainfall anomaly during the two weeks period from 20 May to 2 June shown in Figs. 8(a-b) compared with the forecast rainfall from



Figs. 10(a-l). Observed (TRMM) and forecasts rainfall anomaly (mm/day) from CFSv2, JMA, & MME based on 30 May, 2013 and valid for week-1 (3-9 June), week-2 (10-16 June) and week-3 (17-23 June)

CFSv2 [Figs. 8(c-d)] and JMA model [Figs. 8(e-f)] with JMA model indicating the progress of monsoon northward more realistic as the positive anomaly extended northward upto around 20° N [Fig. 8(f)], whereas, the week-2 forecast in CFSv2 model valid for the period from 27 May-2 June indicated the positive anomaly confined to almost southern tip of India. Thus, the CFSv2 is very clearly indicating slight early onset of monsoon from the forecast of mean rainfall and rainfall anomaly, whereas, the JMA [Figs. 7(e-f) and Figs. 8(e-f)] model mainly indicates the normal onset of monsoon during the week from 27 May-2 June, 2013. The week-1 forecast based on MME valid for 20-26 May, although indicated rainfall belt over southern tip of India [Fig. 7(g)] the positive anomaly was mainly confined to southeast Arabian Sea and not over the Indian land mass [Fig. 8(g)]. The MME week-2 forecast indicate more realistic patterns with very clear onset of monsoon over southern tip of India during the week from 27 May to 2 June, 2013 [Figs. 7(h) and Figs. 8(h)]. Thus, the normal onset of monsoon over Kerala was well captured about 2 weeks in advance in JMA model and MME forecast with slight indication of early onset (although, weak) in CFSv2 was reported. It may be mentioned here that from the beginning of May, 2013 the extended range forecast from NCEP CFSv2 model had consistently indicated slight early onset of monsoon over Kerala compared to its normal date of 1st June and when the objective criteria of increase in zonal wind speed over the Arabian Sea and rainfall over Kerala coast was used for defining the model onset in CFSv2 forecast of 12th May initial condition, the onset over Kerala is found to be 29th May, 2013.



Figa. 11(a-f). Observed weekly rainfall departure along with corrponding weekly rainfall departure over India as a whole during June 2013 with (a) CFSv2, (b) JMA and (c) MME. (d) to (f) same as (a) to (c) but over Northwest (NW) India

4.2. *Extended range forecast of rapid progress of monsoon*

One of the unusual features of monsoon 2013 is the rapid progress of monsoon from southern tip of India. As a result the monsoon was covered by entire India on 16th June and there was also a very unusual heavy rainfall over northwest India particularly in Uttarakhand, which can be seen clearly from the observed weekly mean rainfall from TRMM during 3-9 June, 10-16 June and 17-23 June, 2014 in Figs. 9(a-c) respectively. The observed rainfall during 3-9 June indicates monsoon rainfall over large parts of central India indicating that the monsoon had covered central parts of India as seen from the NLM shown in Fig. 1(a). During the subsequent week the rainfall belt has further moved northward and westward and has covered the entire India during the week from 10-16 June, 2013 [Fig. 9(b)]. The week also indicates heavy rainfall over Uttarakhand and adjoining region. During the subsequent week from 17-23 June the heavy rainfall belt over Uttrakhand and adjoining region slightly shifted eastward [Fig. 9(c)]. The rainfall anomaly during these periods from 3 June to 23 June, 2013 [Figs. 10(a-c)] also indicates positive rainfall anomalies with particularly positively anomaly over entire northern and western parts of India during the period from 10-16 June, 2013 indicating the coverage of monsoon over entire India by 16th June, 2013.

The extended range forecast based on the coupled models in fact had captured this unusual behavior. In order to see the monsoon progress in the coupled model the forecast for three weeks from CFSv2, JMA and MME models based on the initial condition of 30th May, 2013 for mean and anomaly rainfall is shown in Figs. 9(d-l) and Figs. 10(d-l) respectively. As seen from Figs. 9(g-i) and Figs. 10(g-i) the JMA model performed the rapid progress of monsoon very well by indicating the monsoon to cover whole of India during the second week (10-16 June). Though the CFSv2 also captured the rapid progress as indicated [Figs. 10(d-f)] by positive anomaly of rainfall over Uttarakhand region during the period from 10-16 June, however, some parts of Northwest India indicated negative anomaly during the week from 10-16 June [Fig. 10(e)] when compared with observed anomaly shown in Fig. 10(b). Thereby the monsoon was not covered over entire India till 16th June, 2013 in the CFSv2 model based on model forecast of 30th May initial condition. However, the CFSv2 based on the initial condition of 4th June had clearly captured the rapid progress of monsoon northward and coverage of monsoon to entire India with indication of heavy rainfall over many parts of northern India including the state of Uttarakhand during the period from 13-19 June 2013 (Fig. not shown).

The observed heavy rainfall during the week from 17-23 June, 2013 as seen in Fig. 9(c) and Fig. 10(c) also captured well in the model forecast valid for week-3 (days 19-25) in both the models shown in Fig. 9(f) & Fig. 10(f) for CFSv2 and Fig. 9(i) & Fig. 10(i) for JMA. The MME forecast based on the initial condition of 30th May also clearly indicated rapid progress of monsoon and coverage over the entire country by 16th June, 2013 as seen from the mean and anomaly plots of rainfall shown in Figs. 9(k) and Figs. 10(k) respectively. Like incase of individual model, the MME forecast for week-3 valid for the period from 17-23 June also captured the heavy rainfall over many parts of northern India [Fig. 9(l) and Fig. 10(l)]. Thus, the unusual behavior of rapid progress of monsoon during 2013 was very much captured in the coupled models.

4.3. *Extended range forecast of quantitative rainfall*

The rapid progress associated with interaction between a monsoon low and mid-latitude trough has caused unprecedentedly vigorous rainfall over northwest India, resulting in calamitous floods particularly over Uttarakhand. In order to see the performance of this heavy rainfall episode during the onset phase of monsoon the weekly mean rainfall departure for 5 weeks starting from 27 May to 30 June is compared with the corresponding forecasts rainfall departure from CFSv2, JMA and MME for week-1, week-2 and week-3 forecasts. The verification

TABLE 1

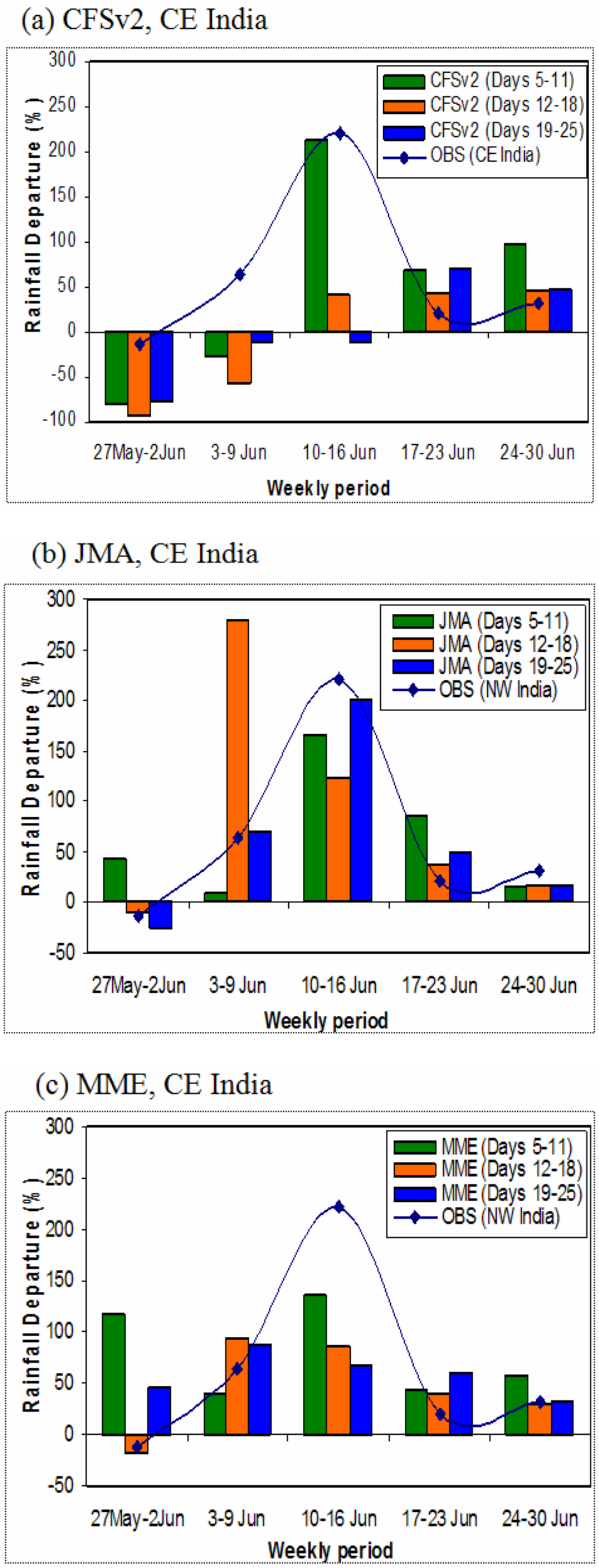
Observed weekly rainfall departure along with corresponding forecast weekly rainfall departure from CFSv2, JMA and MME for the heavy rainfall weeks from 10-16 June and 17-23 June, 2013 over the meteorological subdivision of Uttarakhand

IC = 30 May 2013	Week 2 (days 12-18) June 10-16	Week 3 (days 19-25) June 17-23
Observed Rainfall	322.2%	457.2%
CFSv2 (IC 30 May)	53%	60%
JMA (IC 30 May)	291%	261%
MME (IC 30 May)	92%	97%
	Week 1(days 5-11) June 10-16	Week 2 (days 12-18) June 17-23
Observed Rainfall	322.2%	457.2%
CFSv2 (IC 6 June)	47%	69%
JMA (IC 6 June)	190%	96%
MME (IC 6 June)	83%	77%

of quantitative weekly forecast rainfall from the individual model as well as MME is carried out for observed all India rainfall and rainfall over Northwest India shown in Figs. 6(a&b) respectively. The same is shown in Figs. 11(a-c) for all India rainfall and in Figs. 11(d-f) for Northwest India rainfall. The verification of extremely heavy rainfall forecast from different models over the meteorological subdivision of Uttarakhand obtained from Fig. 6(c) is also carried out and is given in Table 1.

As seen from Fig. 11(a) and Fig. 11(d) the observed rainfall indicate large positive departure from mean (about 80%) over the country as a whole and about 220% over the Northwest India during the week from 10-16 June, 2013. The Northwest India also received rainfall with a positive departure of about 150% during the subsequent week from 17-23 June, 2013. As seen from Fig. 11(a) and Fig. 11(b) the higher rainfall week from 10-16 June, 2013 was well captured in week-1 forecast in CFSv2 as it is close to the observed rainfall departure [Fig. 11(a)], whereas, the JMA model captures the departure with all lead times (week-1, week-2 and week-3 forecasts) as seen from Fig. 11(b). The MME forecast also captures the heavy rainfall week during 10-14 June, 2013 [Fig. 11(c)].

Over the Northwest India the heavy rainfall during two weeks period from 10-16 June and 17-23 June, 2013 was also very well captured in the JMA model [Fig. 11(e)] compared to that of CFSv2 model [Fig. 11(d)]. The MME forecast also captures this event very well, although, the forecast departure is slightly underestimated in the model



Figs. 12(a-c). Observed weekly rainfall departure along with corrponding weekly rainfall departure over India Central (CE) India during June 2013 with (a) CFSv2, (b) JMA and (c) MME

[Fig. 11(f)]. Similarly over the central India also the JMA model slightly performed better compared to CFSv2 model particularly for the week from 10-16 June as seen in Figs. 12(a-c). The JMA EPS model performed better particularly for this rainfall event and it could be due to the better treatment of moist processes in the model. It may be mentioned that in the JMA model the moist process is treated under Prognostic Arakawa-Schubert parameterization, middle-level convection of mass-flux type and large-scale condensation. Some of the previous studies have found useful skill of extended range forecast at least for 2 weeks (Pattanaik, 2014; Pattanaik *et al*., 2013) over all India level, northwest India and central India with the flood over Pakistan and adjoining Northwest India during July-August, 2010 was well captured at least a week in advance (Pattanaik *et al*., 2013). In the present case also the heavy rainfall over Northwest India was well captured. However, as indicated in the study by (Pattanaik, 2014) the quantitative rainfall forecast in the extended range over a smaller spatial domain of meteorological sub-division (India is divided into 36 meteorological subdivisions as indicated in Fig. 1(b) level is very complicated and it is very appropriate to go for category forecast. However, since the particular rainfall event of 2013 over Uttarakhand was unprecedented in nature and has caused several causalities, the extended range forecast on meteorological subdivision of Uttarakhand during the two weeks from 10-16 June and 17-23 June, 2013 are compared with the observed rainfall departure obtained from Fig. 6(c) and is given in Table 1. As seen from Table 1 the model forecast based on the initial conditions of 30 May and 6 June, 2013 and valid for the above two weeks periods (10-16 June and 17-23 June) are reasonably well captured, although, it is underestimated in the individual model forecast. It is further interesting to note that even based on the initial condition of 30 May, 2013 the week-2 and week-3 forecasts have captured the event and particularly more closer to observed departure in the JMA model compared to that of CFSv2 model. The forecast based on 6th June initial condition also reasonably captured the rainfall departure for week-1 and week-2 forecasts valid for the period from 10-16 June and 17-23 June, 2013 respectively.

5. Conclusions

The rapid progress of monsoon northward over India during 2013 is associated with the movement of low pressure area leading to the increase in moisture convergence over northern India. This in conjunction with upper level deep westerly trough during the third week of June led to the unprecedented rainfall over north India during June particularly over the meteorological sub-division of Uttarakhand.

The extended range forecast based on the NCEP CFSv2 coupled model with 16 members, JMA Ensemble Prediction System (EPS) with 50 ensemble members and the MME of these two models clearly captured the rapid progress of monsoon to northwest India with JMA model performed slightly better compared to NCEP CFSv2 in terms of lead time of at least 2 weeks in advance. The active phase of monsoon, particularly during June over northwest India is also captured by the models, however, on sub-division level over Uttarakhand the positive departure of rainfall forecasted by the model was much less than that of observed departure. The JMA model performed better in terms of higher departure of rainfall over Uttarakhand compared to that in CFSv2 model. The underestimation of heavy rainfall in the model is due to the fact that it could not capture the interaction of upper level westerly trough with the low level convergence in the model. However, useful skill of monsoon forecast in the extended range is observed on all India level and also over the northwest India in capturing its rapid progress and associated heavy rainfall.

Acknowledgements

We sincerely acknowledge the National Centre for Environmental Prediction (NCEP) and Japan Meteorological Agency (JMA) for providing the real time forecast products of their coupled models, which have been used for preparing the multi-model ensemble forecast of Indian monsoon rainfall during the southwest monsoon seasons. The authors are also thankful to NASA for making available the daily gridded rainfall data used in the present study. The authors are very much thankful to the Editor for providing very useful suggestions, which helped a lot in improving the quality of the paper.

References

Ananthakrishnan, R., Srinivasan, V., Ramakrishna, A. R. and Jambunathan, R., 1968, "Synoptic features associated with onset of southwest monsoon over Kerala", IMD Forecasting manual, Report IV-18.2.

Ananthakrishnan, R. and Soman, M. K., 1988, "The onset of the southwest monsoon over Kerala 1901-1980", *J. Climatol.*, **8**, 283-296.

Ananthakrishnan, R. and Soman, M. K., 1989, "The dates of onset of the southwest monsoon over Kerala for the period 1870-1900", *Int. J. Climatology.*, **9**, 321-322.

Allaby, Michael, 2002, "Encyclopedia of weather and climate", *Infobase Publishing*, 1-373, ISBN 978-0-8160-4801-4.

Abhilash, S., Sahai, A. K., Pattnaik, S., Goswami, B. N. and Kumar, Arun, 2014, "Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System", *Int. J. Climatology*., **34**, 98-113. DOI:10.1002/joc.3668.

Devi Sunitha, S. and Yadav, B. P., 2014, "Characteristic Features of Southwest Monsoon 2013", In 'Monsoon 2013- A Report', Eds. D. S. Pai and S. C. Bhan. IMD Met. Monograph : Synoptic Meteorology No. : ESSO/IMD/SYNOPTIC MET/01-2014/15, 1-17.

Fasullo, J. and Webster, P. J., 2003, "A Hydrological Definition of Indian Monsoon Onset and Withdrawal", *J. Climate*., **16**, 3200-3211.

Findlater, J., 1969, "A major low level air current near the Indian Ocean during the northern summer", *Quar. J. Roy. Met. Soc.*, **95**, 362-380.

Gruber, A. and Krueger, A. F., 1984, "The status of the NOAA outgoing long-wave radiation dataset", *Bull. American Met. Soc.*, **65**, 958-962.

Houze Jr, R. A., Rasmussen, K. L., Medina, S., Brodzik, S. R. and Romatschke, U., 2011, "Anomalous Atmospheric Events Leading to the summer 2010 Floods in Pakistan", *Bull. American Met. Soc*., **92**, 291-298.

Ishii, M., Shouji, A., Sugimoto, S. and Matsumoto, T., 2005, "Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the KOBE collection", *Int. J. Climatology*., **25**, 865-879.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, Roy and Joseph, Dennis, 1996, "The NCEP/NCAR 40 year re-analysis project", *Bull. American Met. Soc*., **77**, 437-471.

Koteswaram, P., 1958, "The easterly jet stream in the tropics", *Tellus*, **10**, 43-57.

Krishnan, R., Sundaram, S., Swapna, P., Kumar, Vinay, Ayantika, D. C. and Mujumdar, M., 2011, "Crucial role of ocean-atmosphere coupling on the Indian monsoon anomalous response during dipole events", *Climate Dynamics*., **37**, 1-17. DOI 10.1007/s00382-010-0830-2.

Krishnamurti, T. N. and Subrahmanyam, D., 1982, "The 30-50 day mode at 850 hPa during MONEX", *J. Atmos. Sci*., **39**, 2088-2095.

Krishnamurti, T. N. and Ramanathan, Y., 1982, "Sensitivity of the monsoon onset to the differential heating", *J. Atmos. Sci*., **39**, 1290-1306.

Madden, R. and Julian, P., 1971, "Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific", *J. Atmos Sci*., **28**, 702-708.

Madden, R. and Julian, P., 1994, "Observations of the 40-50 day tropical oscillation: A review", *Mon. Wea. Rev.*, **112**, 814-837.

Mohanty, U. C., Dube, S. K. and Singh, M. P., 1983, "A study of heat and moisture budget over the Arabian Sea and their role in the onset and maintenance of summer monsoon", *J. Met. Soc. Japan.*, **61**, 208-221.

Pai, D. S. and Bhan, S. C., 2014, "Monsoon 2013- A Report", *IMD Met. Monograph*: Synoptic Meteorology No: ESSO/IMD/ SYNOPTIC MET/01-2014/15, 1-17.

Pattanaik, D. R., 2003, "The northward moving low frequency mode : A case study of 2001 monsoon season", *Mausam*, **54**, 937-940.

Pattanaik, D. R. and Kumar, Arun, 2010, "Prediction of summer monsoon rainfall over India using the NCEP climate forecast system", *Climate Dynamics*, **34**, 557-572.

Pattanaik, D. R., 2014, "Meteorological subdivisional-level extended range forecast over India during southwest monsoon 2012", *Meteor. Atmos. Phys.*, **124**, 167-182. DOI 10.1007/s00703-014-0308-6.

Pattanaik, D. R., Rathore, L. S. and Kumar, Arun, 2013, "Observed and Forecasted Intraseasonal Activity of Southwest Monsoon Rainfall over India during 2010, 2011 and 2012", *Pure and Applied Geophysics*, **170**, 2305-2328. DOI 10.1007/s00024-013-0670-1.

Pearce, R. P. and Mohanty, U. C., 1984, "Onsets of the Asian summer monsoon 1979-1982", *J. Atmos. Sci*., 41, 1622-1639.

Pisharoty, P. R., 1965, "Evaporation from the Arabian Sea and the Indian southwest monsoon, In: Proceedings of the symposium on meteorological results of the IIOE, Bombay", India Meteorological Department, 43-54.

Raju, P. V. S., Mohanty, U. C. and Bhatla, R., 2005, "Onset Characteristics of the southwest monsoon over India", *Int. J. Climatol.*, **25**, 167-182.

Rao, Y. P., 1976, "Southwest Monsoon : Synoptic Meteorology", IMD Met. Monograph, No. 1/1976, India Meteorological Department, 1-367.

Rao, G. V. and Aksakal, A., 1994, "Characteristics of convection over the Arabian Sea during a period of monsoon onset", *J. Atmos Sci*., **33**, 235-258.

Saha, S., Nadiga, S., Thiaw, C., Wang, J., Wang, W., Zhang, Q., Van den Dool, H. M., Pan, H. L., Moorthi, S., Behringer, D., Stokes, D., Pena, M., Lord, S., White, G., Ebisuzki, W., Peng, P. and Xie, P., 2006, "The NCEP climate forecast system", *J. Climate.*, **19**, 3483-3517.

Soman, M. K. and Krishnakumar, K., 1993, "Space-time evolution of meteorological features associated with the onset of Indian summer monsoon", *Mon. Wea. Rev.*, **121**, 1177-1194.

Saha, Suranjana, Shrinivas, Moorthi, Xingren, Wu, Jiande, Wang, Sudhir, Nadiga, Patrick, Tripp, David, Behringer, Yu-Tai Hou, Hui-ya, Chuang, Mark, Iredell, Michael, Ek, Jesse, Meng, Rongqian, Yang, Huug, van den, Dool, Qin, Zhang, Wanqiu, Wang and Mingyue, Chen, 2014, "The NCEP Climate Forecast System Version 2", *J. Climate*, **27**, 2185-2208. doi: http://dx.doi.org/10.1175/JCLI-D-12-00823.1.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Mon. Wea. Rev.*, **108**, 1840-1853.

Webster, P. J., Toma, V. E. and Kim, H. M., 2011, "Were the 2010 Pakistan floods predictable?", *Geophys. Res. Lett*., **38**, L04806, doi:10.1029/2010GL046346.

World Meteorological Organisation (WMO), 2013, "A Decade of Climate Extreme (2001-2010)", WMO No. 1103, 1-119.

Zhang, C., 2005, "Madden-Julian Oscillation", *Rev Geophys.*, **43**, 1-36.