Extremes in June rainfall during Indian summer monsoons of 2013 and 2014: Observational Analysis and Extended range prediction

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: [10.1002/qj.2730](https://doi.org/10.1002/qj.2730)

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Abstract

The onset/progression phase of Indian summer monsoon (ISM) is very crucial for the agricultural sector of the country as it has strong bearing on the sowing of *kharif* crops, which in turn affects the overall food grain production and hence food security. The recent ISMs of 2013 and 2014 exhibited quite distinct progression phase. While 2013 had one of the fastest advancement in the last 70 years, 2014 witnessed comparatively lethargic progression phase. The major difference was felt in the early monsoon month of June, with 2013 (2014) monthly rainfall being +34% (-43%) of its long period average. Observational investigations reveal that during June 2013, the monsoon trough was very active in its normal position favouring low level positive vorticity generation and moisture convergence, whereas the absence of monsoon trough facilitated the prevalence of a strong low level anticyclonic circulation over central India during June 2014 hampering the northward progression of ISM. It is found that June 2013 (2014) was associated with (a) stronger (weaker) north-south tropospheric temperature (TT) gradient with positive (negative) TT anomalies over Eurasia and north of 60°N, (b) colder (warmer) SST anomalies over equatorial Indian Ocean, northwestern Arabian Sea and equatorial eastern Pacific, (c) stronger (weaker) monsoonal Hadley circulation, and (d) stronger (weaker) Walker circulation in response to the colder (warmer) SST anomalies over equatorial Pacific. The study also examines the skill of an Ensemble Prediction System (EPS) in predicting the observed contrasting behaviour during June 2013/2014 on extended range (~15-20 days in advance) in real time. The EPS not only forecasted the observed discrepancy, but also predicted the influential

role of large scale meteorological conditions that were prevalent during June 2013 (2014), thus advocating the remarkable skill of the EPS in predicting June extremes.

Keywords

Indian summer monsoon, June extreme, El-Niño, La-Niña, Ensemble Prediction System

1. Introduction

Indian summer monsoon (ISM) is one of the most awaited weather phenomena over the region due to its high socio-economic and hydrological impacts. ISM commences in the month of June over the country and the start of agricultural activities over various parts of the country coincides with the advance of monsoon over the region. As most of the farmlands are rain-fed, monsoon is critical to the food sufficiency and quality of life for the country and is said to be the driver of Indian agriculture (IMD, 2013). Onset phase of monsoon, especially the June rainfall, has strong bearing on the *kharif* or *monsoon* crops, which are totally dependent on the rainfall for their growth and development. Therefore, any fluctuations in the spatio-temporal distribution or quantity of the monsoon rains may lead to conditions of floods or droughts causing the agricultural sector to adversely suffer (IMD, 2014), which in turn affect the overall economy, food inflation and therefore the overall quality and cost of living for the general population in India.

In general, monsoon makes its onset over the southern tip of peninsular India around 01 June and progresses northward to cover the entire country by 15 July (Pai and Rajeevan, 2009). However, the onset and progression of monsoon exhibit large amount of interannual variability. In some years they are timely, whereas during some years they are faster or slower. After the

onset, monsoon advance is not a smooth process but is punctuated by one to three stagnations at different latitudes or longitudes (Sikka, 2011). The stagnations could be caused by the influence of eastward moving upper level westerly troughs in the subtropical latitudes (Biswas *et al.*, 1998) or cessation in the formation of low pressure systems (LPS) in the surrounding seas or within the monsoon trough (Sikka, 2011). During some years, the advancement occurs rapidly and the monsoon covers from Kerala to northwest India in just 15-20 days or so. Similarly, there are years when after a prolonged stagnation in monsoon advance, the next progression of monsoon is quite rapid due to the overlapping formation of LPSs (Sikka, 2011).

The ISMs of 2013 and 2014 were quite distinct in their progression phase. 2013 witnessed the fastest pace of advance of ISM in the last 70 years (IMD, 2013; Joseph *et al.*, 2013, 2014). Monsoon covered the entire country in just 16 days after its onset over Kerala on 01 June, i.e., by 16 June, which is one month ahead of its climatological date. On the other hand, after a delayed onset over Kerala on 06 June, the 2014 monsoon exhibited a sluggish northward progression owing to a prolonged hiatus which occurred after a few days of its onset. Monsoon covered the whole country by 17 July in 2014.

The major difference in the progression phase during these two years was felt in the early monsoon month of June, in which the long term mean (LTM) monthly rainfall is 163.5 mm (source: http://www.imdpune.gov.in/mons_monitor/mm_index.html) all over India. The rainfall over the country during the month of June in 2013 was 134% of its LTM (IMD, 2013), while that of June 2014 was only 56.5% of its climatology (source: http://www.imdpune.gov.in/mons_monitor/mm_index.html). Although there are other years

when the June rainfall was >30% of its LTM (for e.g., 2001 in the last 14-year period: 2001-2014; **Table 1**), June 2013 was exceptional due to its rapid progression phase. The duration of 42 days (as in the case of 2014) is not unusual for monsoon to cover the entire country (please see **Table 1**), however a deficiency of ~43% in June rainfall is rather infrequent. Such a dearth was observed recently during 2009, when the June deficit was ~47%.

Joseph *et al.* (2013, 2014) has shown that large scale conditions were very active during June 2013. They argued that the interaction between a monsoonal low pressure system which provided increased low level convergence and abundant moisture, and a midlatitude westerly trough which generated strong upper level divergence has provided conditions conducive for large scale convection and widespread monsoon rains over northwest India. They hypothesized that these large scale conditions helped monsoon to cover the entire country and facilitated the occurrence of the heavy rainfall event in the orographic region of Uttarakhand.

During June 2014, the daily weather bulletins issued by India Meteorological Department (IMD; the official weather forecasting agency under Govt. of India) indicated that the monsoon trough was absent and an anticyclonic circulation was prevalent over central India (CI). This anticyclonic circulation was persistent throughout the month of June, thus delaying the progression of monsoon to the central and northern parts of the country. It affected the agricultural sector adversely by forcing the farmers to shift to short duration varieties; from cash crops to food crops or even fodder (IMD, 2014). According to IMD, a reduction of about 3.67 million tonnes occurred in rice production in 2014 on all India level, compared to 2013. The production of maize also decreased by 1.67 million tonnes (IMD, 2014). On the other hand, the

significant and well distributed rainfall received during the onset phase of 2013 ISM helped the farmers to sow and transplant the rice and other major crops at the right time in different parts of the country (IMD, 2013).

Considering the above-mentioned impacts of June rainfall on agricultural sector in these two consecutive years, it is worthwhile to explore the underlying mechanisms that shaped the observed discrepancy, and to examine the predictability of the observed contrasting behavior and associated features in the extended range (i.e., 10-20 days in advance) time scale. Although Joseph *et al.* (2013, 2014) provided some insights on the progression of monsoon in 2013, their study focused mainly on the Uttarakhand heavy rainfall event and hence did not provide a detailed study on the background monsoon conditions prevailed during June 2013. Additionally, no detailed documentation is available on the role of meteorological conditions in prevailing the anticyclonic circulation over Indian region during June 2014. Therefore, the present study addresses the following issues: (i) the role of local as well as large scale meteorological conditions that were responsible for the observed fast (slow) progression of monsoon in the month of June 2013 (2014), (ii) whether similar meteorological conditions as that of June 2013 (2014) were existent during June 2001 (2009) when the June rainfall departure was +35% (-47%) and, (iii) whether the observed contrasting behavior was predictable on extended range in real time and if so, whether it helped the farmers to plan their agricultural activities in an efficient way.

The extended range prediction (ERP) group of Indian Institute of Tropical Meteorology (IITM), Pune, India has indigenously developed an Ensemble Prediction System (EPS; Abhilash

et al., 2012, 2014b; Borah *et al.*, 2013; Sahai *et al.*, 2013) for the prediction of active/break spells of ISM in 2011, under the National Monsoon Mission program (<http://www.tropmet.res.in/monsoon/>) initiated by the Government of India. The EPS is based on the ocean-atmosphere coupled Climate Forecast System version 2 (CFSv2) model (Saha *et al.*, 2014). The experimental forecasts are available at 5 day interval during the monsoon season from 2001 onwards and are being disseminated at the IITM website <http://www.tropmet.res.in/erpas/> on real time basis since 2013. The present study uses the forecasts from this CFSv2 based EPS and details of the EPS is given in the subsequent section (Sec. 2).

2. Model and Observational datasets

To assess the predictability aspects, we use the NCEP CFSv2 (Saha *et al.*, 2014), with the Global Forecast System (GFS) as its atmospheric component, coupled to the GFDL Modular Ocean Model version 4p0d (MOM4; Griffies *et al.*, 2004), a four-layer Noah land surface model (Ek *et al.*, 2003) and a two-layer sea ice model (Wu *et al.*, 2005). In this study, the outputs from the multimodel ensemble (MME) generated from the CFSv2 based Grand Ensemble Prediction System (CGEPS; Abhilash *et al.*, 2015a; b) is used. The CGEPS includes three sub-ensembles, from CFSv2 run at T126 (~100km; hereafter termed as CFS126) and T382 (~38 km; hereafter termed as CFS382) horizontal resolutions, plus the GFS forced with bias corrected SST from CFS126 (hereafter termed as GFSbc). CGEPS MME has 21 ensemble members of GFSbc and 11 members each of CFS126 and CFS382. Every year, each of these ensembles are run for 45 days lead time every 5 days, starting from 16 May to 28 September. For the experimental details and

skills of GFSbc, CFS126 and CFS382, refer Abhilash *et al.* (2012; 2014 a; b) and Sahai *et al.* (2015) respectively. Each of the ensemble members of the MME are generated by slightly perturbing the initial atmospheric conditions with a random matrix (random number at each grid point) generated from a random seed. In order to center the ensemble seeding around an unperturbed analysis, Gaussian random numbers with mean 0 and unit standard deviation are used to rescale wind, temperature and moisture differences between a short term forecast and its corresponding analysis. It is ensured that amplitude of perturbation varies in accordance with the uncertainty in the analysis. Details on the formulation of EPS can be found in Abhilash *et al.* (2012, 2014b) and Borah *et al.* (2013).

For the present study, the observational datasets used are: daily NOAA high resolution Sea Surface Temperature (SST) dataset (Reynolds *et al.*, 2007) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, (available at <http://www.esrl.noaa.gov/psd/>), the daily rainfall dataset from TRMM (Huffman *et al.*, 2007), IMD-TRMM merged rainfall dataset (Mitra *et al.*, 2009) and atmospheric fields from National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis datasets (Kalnay *et al.*, 1996). The meteorological parameters utilized from NCEP/NCAR reanalysis for the study are: zonal, meridional and vertical components of wind, specific humidity, air temperature and geopotential height at pressure levels and also mean sea level pressure (mslp). Additionally, the Moist Static Energy (MSE), Tropospheric Temperature (TT), Kinetic Energy (KE) of total wind as well as rotational wind, velocity potential and divergent wind have been computed.

The anomalies of various parameters, except rainfall are calculated based on the daily mean climatology of 12 years (2001-2012) for both model as well as observations to maintain commonality and ease of comparison among the datasets.

3. Results and Discussion

In this section, we analyze various meteorological parameters which might provide an insight into the local as well as large scale conditions prevalent during June 2013/2014.

3.1. Observed features during June

It has been mentioned earlier that the rainfall over the Indian subcontinent was surplus during June 2013, while it was scarce during June 2014; and a low level cyclonic (anticyclonic) circulation was prevalent over the Indian subcontinent during June 2013 (2014). To elucidate this, the rainfall anomaly and KE of rotational component of 850 hPa wind are plotted and shown in **Figure 1** along with the streamlines of total wind anomalies. The figure reveals that during June 2013, the rainfall was largely positive over most parts of the country making it +34% of LTM (**Figure 1a**), while the rainfall was deficient (evident from negative rainfall anomalies) all over the country (-43% of its LTM) in June 2014 (**Figure 1c**). Also, the cross equatorial flow was very strong and the monsoon trough was active over CI in June 2013, favoring low level moisture convergence (**Figure 1b**). During June 2014, the cross equatorial flow was very weak and an intense anomalous anticyclonic circulation was ubiquitous over CI region (**Figure 1d**). It could be contemplated that the prevalence of this anomalous anticyclonic circulation hindered the northward progression of monsoon in June 2014. The presence of anticyclonic circulation over CI can lead to the suppression of convection over the region, as

illustrated in **Figure 2b** that delineates the time-height evolution of anomalous omega (pressure vertical velocity in hPa s⁻¹ multiplied by -1.0) over the region 70°-85°E; 15°-25°N. It is appealing that entirely contrasting omega anomalies are noticed over the region during June 2013 and 2014. The descending motion owing to the anticyclonic circulation anomalies at the lower levels (**Figure 2b**) and the convergence at the upper levels (please refer **Figure 4d**) has been very strong over the region till first week of July 2014. The contrasting features are further evident in **Figure 2c** and **d**, that portrays the monsoonal Hadley circulation during June. During June 2013, the monsoonal Hadley circulation, which is generally characterized with ascending motion over Indian subcontinent and descending motion over the south equatorial Indian Ocean, was very strong (**Figure 2c**). In the case of June 2014, strong anomalous subsidence (which is associated with the anticyclone over the region) prevailed over the Indian region while anomalous upward motion was noticed south of the equator (**Figure 2d**). Thus the atmosphere was very unstable (stable) over the Indian region during June 2013 (2014).

Large-scale organized convection, such as the ISM rainfall, is associated with reduced vertical static stability. The MSE of the surface layer is a useful measure of vertical instability and is defined as:

$$MSE = C_p T + gz + L_c q \quad \text{--- (1)}$$

where, the first two terms on the RHS represents the dry static energy and the third term represents the moisture term. Chakraborty *et al.* (2006) showed that the convective available potential energy (CAPE) becomes positive and increases rapidly only after the surface MSE reaches a threshold value of 346 kJ/kg. It is found that during June 2013, the MSE values over CI

region (70° - 85° E; 15° - 25° N) are always above the threshold value, whereas they are mostly below the threshold value during June 2014 (Figure not shown). The spatial patterns of MSE anomalies during June 2013 and 2014 are shown in **Figures 3a** and **c** respectively. The figure clearly brings out the asymmetry in these two years. During June 2013, the anomalies are largely positive over most parts of the country, whereas the anomalies are negative over CI during June 2014. It is evident from the figure that enormous amount of instability was existent during June 2013, compared to 2014, which might have helped monsoon to cover the entire country in a faster pace during 2013. The vertically integrated (from surface to 500 hPa level) moisture anomalies during June 2013 and 2014 are shown plotted in **Figures 3b** and **d** respectively. The positive (negative) precipitable water anomalies are noticed during June 2013 (2014), which could be attributed to the fact that the moisture term is the major contributor in the MSE equation (Chakraborty *et al.*, 2006). Both the negative MSE and moisture anomalies are indicative of the presence of a stable atmosphere over CI during June 2014 that might have contributed to the hiatus in the northward progression of monsoon observed during the period.

From the above discussion, it could be speculated that the preponderance of the anomalous anticyclonic circulation and the absence of monsoon trough at low level has inhibited the northward progression of monsoon in June 2014. Presence of such anomalous anticyclonic circulation over CI is generally observed during typical break monsoon periods (Krishnan *et al.*, 2000; Joseph *et al.*, 2009 among others). The northward advancement of monsoon was favored only after the dissipation of the anticyclonic circulation, with the establishment of monsoon

trough. Thus, the analyses raise an interesting question - what caused the prevalence of these observed features? This will be addressed in the forthcoming section of the paper.

3.2. Large scale influence on the observed disparity

3.2.1. Global SST

Suppressed (enhanced) convection over Indian region is known to be related to the warmer (colder) SST anomalies over equatorial Indo-Pacific oceanic regions (Ashok *et al.*, 2012; Meehl, 1987; Rao and Goswami, 1998; Rajeevan and McPhaden, 2004 among others). Hence SST anomalies over the Indo-Pacific region during June 2013 and 2014 have been plotted and shown in **Figure 4a** and **b**. It is remarkable to note that cold (warm) anomalies indicative of La-Niña (El-Niño) conditions are noticed over the equatorial eastern Pacific during June 2013 (2014). In conjunction with the cold (warm) SST anomalies over the equatorial Pacific, negative (positive) rainfall anomalies are observed over the region during June 2013 (2014) (Figure not shown). Rainfall anomalies of opposite polarity to that of equatorial Pacific Ocean are seen over Indian subcontinent, indicating their out-of-phase relationship. In the case of June 2013, the weak La-Niña conditions and associated upper level convergence (**Figure 4c**) in the eastern Pacific could have intensified the Walker circulation (**Figure 4e**) that is favorable for monsoon rains over India through modulation of monsoonal Hadley circulation. Interestingly, the warm anomalies extend across the equatorial Pacific during June 2014 exhibiting a basin wide warming signature (**Figure 4b**). It is noted that the warming was ubiquitous over the region in the pre-monsoon months also (Figure not shown). Such basin wide warming can lead to suppressed convection over Indian region as in the case of June 2009 (Ratnam *et al.*, 2010;

Ashok *et al.*, 2012) when the June rainfall departure over the country was -47%. In conjunction with this basin wide warming, anomalous upward motion is observed almost everywhere in the tropical Pacific (**Figure 4f**). This is indicative of the anomalously weak Walker circulation over the region. It is found that the anomalous outflow of divergent wind over the central and eastern equatorial Pacific region, which is associated with the convection due to warm SST anomalies over the region, has an anomalous subsiding branch over the Indian subcontinent (**Figure 4d**). This is a typical El-Niño effect (Annamalai, 2010; Slingo and Annamalai, 2000) and similar conditions were prevalent over the Indo-Pacific region during 2009 (Ratnam *et al.*, 2010). Joseph *et al.* (1994) and Ju and Slingo (1995) suggested that years with warm SST anomalies in the equatorial central and east Pacific Ocean have a weaker monsoon circulation and a delayed onset. Thus it can be envisaged that although some studies claim that the ENSO-monsoon relationship has weakened (for e.g., Kumar *et al.*, 1999), the influence of equatorial Pacific Ocean on the ISM remains relevant even in the recent times, as evident in June 2014.

Another important disparity noticed during June 2013 (2014) is the presence of cold (warm) SST anomalies over northwestern Arabian Sea (AS) (please refer **Figure 4a** and **b**). Such anomalous warming (cooling) in the northwestern AS is unfavorable (favorable) for monsoon activity over Indian subcontinent (Ramesh and Krishnan, 2005; Li and Yanai, 1996). The warm SSTs over the region during June 2014 seems to be generated by the weak monsoonal westerly winds (see **Figure 1d**) which in turn contributed to the reduced upwelling and hence inhibited the cooling in the northwestern AS. On the contrary, the strong monsoonal currents during June 2013 might have led to strong upwelling and thereby contributed to cooling in the northern AS.

The warming (cooling) over northwestern AS during June 2014 (2013) is noticed during June 2009 (2001) also (**Suppl. Figure S1**).

It is to be noted that the warm anomalies during June 2014 preponderated all-across the Indian Ocean (**Figure 4b**), suggesting a basin wide warming. The warming was evident even in the pre-monsoon months (Figure not shown). Joseph *et al.* (1994) suggested that the existence of such warm SST anomalies over the equatorial Indian Ocean can adversely affect the ISM strength by delaying its onset and advancement. They also hypothesized that such delay in the onset and advancement of ISM associated with the Indian Ocean warm SSTs is more pronounced during the onset phase of El-Niño, as experienced in June 2014.

3.2.2. Tropospheric Temperature

It is well-known that the seasonal heating of the elevated surface of the Tibetan Plateau, and the consequent reversal of tropospheric temperature (TT; defined as air temperature averaged between 600 and 200 hPa by Xavier *et al.*, 2007) along with the pressure gradients south of 35°N, trigger the large-scale change in the general circulation over Asia and the abrupt burst of the monsoon over the Indian subcontinent (Flohn, 1960; Xavier *et al.*, 2007). The strength of the ISM is closely related to the sign of the meridional gradient of TT (defined by Xavier *et al.*, 2007 as the difference of TT values between the northern box 40°–100°E; 5°–35°N and the southern box 40°–100°E; 15°S–5°N). Therefore, the TT gradient during 2013 and 2014 is plotted in Figure 5. It is worthwhile to note that the TT gradient during 2013 is well above climatology from second half of May onwards. Conversely during 2014, the gradient is well below the climatology till second half of June, and it became positive from negative by 06 June

(the date on which monsoon onset over Kerala occurred). The large values of TT gradient during 2013 could be attributed to the warm TT anomalies present in the northern hemisphere, compared to the south of equator (**Suppl. Figure S2a**). It is important to note that the TT anomalies are warmer in the equatorial region during 2014 compared to 2013 (**Suppl. Figure S2b**). Hence it could be concluded that it is the north-south gradient of TT, rather than the actual TT values, that are critical in modulating the strength of ISM.

Xavier *et al.* (2007) indicated that the warmer SSTs over equatorial Pacific Ocean during El-Niño years can regulate the ISM strength through the atmospheric response to the diabatic heating associated with the SST, leading to a substantial reduction of the meridional gradient of TT over the Indian monsoon region and this is evident in June 2014. The converse is true for La-Niña years. They also advocated that the negative TT anomaly over Eurasia during pre-monsoon months forced by El-Niño heating delays the onset of ISM. The January-May averaged TT anomalies during 2013 and 2014 have been plotted in **Suppl. Figure S2c** and **d** respectively. Interestingly, negative TT anomalies are seen over Eurasian region during 2014 (**Suppl. Figure S2d**). This cooling signature is evident in the monthly averaged TT anomalies plotted for individual months from January-May (Figure not shown). The negative TT anomalies preponderate over the midlatitudes even during June 2014 (**Suppl. Figure S2b**). This proved to be detrimental for the monsoon activity over Indian subcontinent. As suggested by Xavier *et al.* (2007), these negative TT anomalies over Eurasia in the pre-monsoon months as well as in June might have weakened the north-south TT gradient, thereby delaying the onset of 2014 monsoon and weakening the monsoon activity during June. These weakened TT gradients could also be

attributed to the warming in the tropical Pacific during premonsoon months (Figure not shown). In contrast, the anomalously warmer TT anomalies over Eurasian region supported the enhancement of monsoon activity over Indian region during June 2013.

The strengthened (weakened) TT gradients observed during June 2013 (2014) were noticed during June 2001 (2009) also (**Suppl. Figure S3**).

3.2.3. Midlatitude Influence

As the monsoon sets in and progresses, the subtropical westerlies in the upper troposphere move northward away from the Indian region and the tropical easterlies dominate over the region. However, at times, these upper tropospheric westerlies associated with the midlatitude weather systems (like troughs) intrude southwards to the Indian region and affect the ISM. They can adversely affect the ISM by causing break-like conditions over Indian region (Ramaswamy, 1962; Krishnan *et al.*, 2009). Krishnamurti *et al.* (2010) showed that the intrusion of westerlies associated with the midlatitude troughs and the associated cold air advection was instrumental in generating the subdued convective activity over the Indian region during June 2009. It has been noted from the previous sections that June 2014 share some commonality with June 2009. Hence, we plotted the zonal component of 200 hPa wind along with its magnitude in **Figure 6** for a period of 10 days each (i.e., 01-10 June, 11-20 June and 21-30 June). The prevalence of midlatitude westerlies over Indian region is evident during almost whole of June 2014. Interestingly, the intrusion is noticed during 2013 from 11-20 June. The heavy rainfall event over Uttarakhand occurred in concurrence with this intrusion. Joseph *et al.* (2013, 2014) indicated that the interaction between the midlatitude westerly trough and a monsoonal low

pressure system played seminal role in generating this extreme event over the orographic region. They hypothesized that the low pressure system provided huge amount of moisture to the region and the westerly trough intrusion has instigated the heavy rainfall event in the moist environment, as suggested by Li and Fu (2006). Thus it is found that the same meteorological condition, i.e., the midlatitude westerly intrusion, has forced the generation of contrasting phenomena over Indian region during June 2013 and 2014. This finding supports the theory proposed by Sikka (2011). According to his study, the interaction between ISM and the upper tropospheric westerlies associated with the midlatitude troughs and its influence on the ISM depends upon the status of the monsoon activity at the time of beginning of interaction period and also the phase of the Rossby wave. The study proposed that if the monsoon is in its weakening phase, the approach of a westerly trough would aggravate ‘break conditions’ in the monsoon, while if the monsoon is in intensifying stage, such interaction would result in enhancement of rainfall over Indian subcontinent. During June 2013, the background moisture was ample (as evident from **Figure 3b**) whilst dry conditions were prevalent over most parts of the country during June 2014 (**Figure 3d**). Therefore, it could be contemplated the midlatitude westerly intrusion intensified the active (break) situations during June 2013 (2014), as suggested by Sikka (2011).

The westerly trough incursions during June 2014 could be attributed to the El-Niño conditions that were developing in the Pacific (Krishnan *et al.*, 1998; Hoskins and Wang, 2005) or to the recent increasing Arctic Amplification (Screen and Simmonds, 2010; Pithan and Mauritsen, 2014). Both of these factors can induce north-south meandering of subtropical

westerly jetstreams, which in turn cause the troughs embedded in the westerlies to intrude southwards to the tropical region affecting the tropical climate.

3.3. Extended Range Prediction of the observed disparity

In Sec. 3.2, the observed local as well as large scale features during June 2013 and 2014 have been discussed and it is found that the contrasting rainfall could be framed by the large scale warming in the tropical Pacific together with the midlatitude influence, which might also be linked to the Pacific warming to some extent. Now, it is worthy to examine whether this contrasting behaviour had some predictability on extended range. As mentioned earlier, the CGEPS MME used in this study has been employed to generate the real-time experimental extended range forecasts during 2013 and 2014 ISMs, and Borah *et al.*, (2014) and Sahai *et al.*, (2015) has shown that the MME could reasonably predict the intraseasonal variations during 2013 and 2014 ISMs respectively. However, these studies analysed the general proficiency of the MME in predicting the ISMs with emphasis to selected active/break spells, and did not study the June extremes. Therefore, the skill of the CGEPS MME in predicting the contrasting progression phase of ISM and the observed June extremes during 2013 and 2014 has been evaluated here.

Prior to this evaluation, it is advisable to examine the ability of the MME in predicting June extremes in general. As mentioned in **Table-1**, there are 4 cases of June extremes during 2001-14. In 2001 and 2013, the June rainfall was exceptionally positive (+35.6% and +34.4% respectively); whereas, the June rainfall was remarkably negative during 2009 and 2014 (-47.2% and -43.5% correspondingly). **Figure 7** depicts the pentad-wise percentage departure of rainfall over monsoon zone (defined by Rajeevan *et al.*, 2010) for observation as well as the prediction in

pentad 1 to pentad 4 (P1-P4; 05-20 day) lead times. It is worthwhile to note that the CFSv2 based MME could predict the extremes of June rainfall in almost all pentad leads with great fidelity. This gives us the confidence to use this MME for the detailed study of contrasting progression phase of ISM during June 2013 and 2014.

3.3.1. Predicted features during June 2013 and 2014

Figure 8 depicts the predicted rainfall anomalies and low level (850 hPa) wind along with the KE of its rotational component, from P1-P4 pentad leads. It is clear from **Figure 8a-h** that the MME could predict the contrasting June rainfall anomalies during 2013 and 2014 convincingly in all the pentad leads, albeit the anomalies weaken with increasing lead. **Figure 8i-p** exhibits the KE of rotational component of 850 hPa wind along with the streamlines of total wind anomalies. The strengthened (weakened) cross equatorial flow during June 2013 (2014) was predicted by the MME in all the pentad leads. Although the cyclonic (anticyclonic) circulation is well defined in observations during 2013 (2014), it is not distinct in MME. However, the inflow towards (outflow from) central Indian region is clear in MME. This becomes discernible in **Figure 9a-h** that shows the time-height evolution of anomalous omega (pressure vertical velocity in hPa s^{-1} multiplied by -1.0) over the CI region 70° - 85° E; 15° - 25° N. It is appealing that entirely contrasting omega anomalies noticed over the region in observations during June 2013 and 2014 (**Figure 2a** and **b**) are forecasted by the MME realistically in almost all pentad leads. The ascending motion corresponding to the cyclonic circulation anomalies during June 2013 is forecasted by the MME in P1-P4 pentad leads (**Figure 9a-d**). Moreover, the descending motion over central India associated with the anticyclonic circulation anomalies

during June 2014 is predicted at all pentad leads realistically (**Figure 9e-h**). Similar results are seen in **Figure 9i-p** that depicts the monsoonal Hadley circulation during June 2013/14. During June 2013, the monsoonal Hadley circulation, which is generally characterized with ascending motion over Indian subcontinent and descending motion over the south equatorial Indian Ocean, was very strong (**Figure 2c**). In the case of June 2014, strong anomalous subsidence (which is associated with the anticyclone over the region) prevailed over the Indian region while anomalous upward motion was noticed south of the equator (**Figure 2d**). It is interesting to note that these contrasting features during June 2013 and 2014 are well predicted by the MME up to fourth pentad lead (**Figure 9i-p**).

It is clear from this subsection that the MME based on CFSv2 could realistically predict the observed features during June 2013 and 2014. It is shown in Sec. 3.2 that these observed contrasting features were governed by large scale meteorological conditions. In the forthcoming subsection, we examine whether the MME could predict the influential role of large scale conditions correctly.

3.3.2. Role of large scale conditions as predicted by the MME

It is found in **Figure 4** that anomalous inflow (outflow) of divergent wind was existent over the equatorial eastern Pacific during June 2013 (2014) in response with the cold (warm) anomalies indicative of La-Niña (El-Niño) conditions over the region. It is seen that the MME could predict the anomalous inflow over the central Pacific in response to the low level divergence in the region in the first two pentads, but failed to predict the inflow over eastern Pacific during June 2013(**Figure 10a-d**). At longer leads, the inflow over eastern Pacific was

predicted to some extent. Altogether, the response of the MME to the cooler event in the Pacific is quite different from the observation. On the other hand, it could predict the anomalous outflow associated with the low level convergence during June 2014, at all pentad leads (**Figure 10e-h**). This indicates that the MME could predict the anomalous warming of equatorial Pacific during June 2014 in advance, indicating the skewness of the MME to the El-Niño events. This becomes more discernible in **Figure 10m-p** that shows the strong upward motion over the equatorial Pacific during June 2014 suggestive of weakened Walker circulation. The Walker circulation response of the MME during June 2013 is quite distinct from the observations.

Another important characteristic noticed during June 2013 (2014) was the stronger (weaker) TT gradient (**Figure 5**). It is interesting to note that even with inherent cold bias in temperature, the MME could predict this disparity with great fidelity (**Figure 11**) in all the pentad leads. It is also found that the strong (weak) TT values to the north of the equator during June 2013 (2014) are predicted by the MME from P1 to P4 leads (**Suppl. Figure S4**).

It has been shown in Sec. 3.2.3 and **Figure 6** that southward incursion of troughs embedded in the midlatitude westerlies affected the monsoon activity during June 2013 and 2014 in a different way. In June 2013, when the monsoon was in intensifying stage, the interaction helped in the enhancement of rainfall over Indian subcontinent, while in June 2014 when the monsoon was in weakening phase, the approach of the westerly trough intensified the ‘break conditions’ in the monsoon. The midlatitude westerly intrusion and the associated vigorous ISM activity was noticed in mid June in concurrence with the Uttarakhand heavy rainfall event and hence we examined the midlatitude influence on the ISM activity in a period of 10 days each in

Figure 6. Therefore, we assessed the skill of the MME in predicting the midlatitude influence in the same way and shown plotted in **Figure 12** as four subpanels for P1 to P4 lead times (**Figures 12a-f, 12g-l, 12m-r** and **12s-x** are for P1, P2, P3 and P4 lead times respectively). The southward intrusion of midlatitude westerlies during June 2014 has been predicted by the MME in all the pentad leads; however, the intrusion during 11-20 June 2013, which was instrumental in generating the Uttarakhand event, is not predicted by the MME, except at P1 lead (**Figure 12**).

Thus, it is apparent from this subsection that the large scale meteorological conditions that were observed during the contrasting June extremes during 2013/14, especially 2014 were predicted reasonably by the MME. It is thus ensured that the MME could predict the observed disparity for the right reasons.

4. Conclusions

The present study investigates the scientific rationale as well as the predictability aspects of the observed contrasting progression phase of ISM during 2013 and 2014, with special emphasis on the disparity noticed in the early monsoon month of June. It is identified that during June 2013, the cross equatorial flow was very strong and brought ample amount of moisture to the Indian region, favoring low level moisture convergence and prevalence of positive MSE anomalies (which is indicative of large scale instability) over the region. The weak La-Niña conditions over eastern equatorial Pacific, warmer SSTs over western AS and warmer TT anomalies over the Eurasian region also provided an environment that is conducive for large scale convection over the Indian region. Additionally, a midlatitude westerly trough interacted with a monsoonal low pressure system in this highly unstable environment around 16 June

(Joseph *et al.*, 2013, 2014). These large scale conditions helped monsoon to cover the entire country by 16 June. In contrast, during June 2014, the cross-equatorial flow was weak owing to weak north-south gradient of TT. The weak TT gradients could be ascribed to the colder TT anomalies over Eurasia and warmer troposphere over equatorial regions. The reduction of the meridional gradient of TT over the Indian monsoon region might also be related to the atmospheric response associated with the basin wide warming noticed in the equatorial Pacific in the pre-monsoon months and June. The warmer SSTs over the equatorial Indian Ocean and western AS also proved to be fatal for the ISM activity in June. Moreover, the pervasiveness of midlatitude westerlies over the Indian region (which is unfavorable for ISM activity) was noticed during June 2014. All these factors contributed to the existence of negative MSE anomalies over the Indian region, which subsequently favored the absence of monsoon trough and the formation as well as the sustenance of anticyclonic circulation over CI region.

Now there remains an interesting question - what caused the increased wave activity in the midlatitudes during 2014, which in turn made the midlatitudes colder and contributed to the weakening of meridional TT gradient? A recent study by Coumou *et al.* (2014) provided evidences for the weakening of the zonal mean midlatitude westerly jets and an amplification of quasi-stationary waves by resonance between free and forced waves in the midlatitude waveguides, in the recent decade. They argued that the rapid warming in the Arctic during the past few decades (termed as Arctic Amplification; Screen and Simmonds, 2010; Pithan and Mauritsen, 2014, among others) and associated changes in the zonal mean zonal wind have created favorable conditions for double jet formation in the extratropics, which promotes the

development of resonant flow regimes (i.e., larger north-south meanders in the flow) over the region. As this meandering develops, troughs may be expected to extend further southwards bringing in cold polar air to the tropics and ridges push the warm tropical air further northwards. The southward penetration of these troughs to the tropical regions can cause the mid-latitude weather systems to be more persistent (Francis and Vavrus, 2012; Cohen *et al.* 2014; Coumou *et al.*, 2014; Francis and Skific, 2015) and can modulate the ISM activity significantly. However, the manner in which this interaction modulates the ISM activity depends upon the background conditions prevailing over the Indian region at the time of interaction (Sikka, 2011), as noticed during June 2013 and 2014.

Krishnan *et al.* (1998) and Hoskins and Wang (2005) indicated that large-scale tropical heating such as El-Niño can support the generation of stationary Rossby waves in the midlatitudes through Rossby wave dispersion from tropics to midlatitudes. During El Nino events, polar jet stream diverges from its usual path and more mid-latitude westerly troughs move across north India. The southward penetration of these midlatitude waves may lead to cold air incursion into the tropical domain. It was noted from **Figure 4b** that El-Niño conditions were prevalent in the equatorial tropical Pacific during June 2014. Hence it could be envisaged that the SST anomalies also might have contributed to the increased wave activity in the midlatitudes.

It is to be noted that the large scale conditions observed during June 2013 (2014) share some commonality with those during June 2001 (2009), when the rainfall departure for the month was +35% (-47%). During both June 2001 and 2013, the weak La-Niña conditions were prevailing over eastern equatorial Pacific (refer **Figure 4a** and **Suppl. Figure S1**). Moreover, the

TT gradients were very strong (well above climatology) from second half of May onwards during both these years (**Figure 5** and **Suppl. Figure S3**). Regarding June 2009 and 2014, both the years witnessed a basin wide warming over the equatorial Indo-Pacific Oceans (refer **Figure 4b** and **Suppl. Figure S1**), which in turn weakened the ISM activity over Indian region through slackening of the equatorial Walker circulation and subsequent modulation of the monsoon Hadley circulation. The warmer SSTs also contributed to the weakening of meridional TT gradient in these two years (see **Figure 5** and **Suppl. Figure S3**). During both June 2009 and 2014, the southward incursion of troughs embedded in the midlatitude westerlies was identified (please refer Krishnamurti *et al.*, 2010 and **Figure 6**). This westerly incursion also favored the decreased monsoon activity during June 2009 and 2014. An interesting question that arises from the above analysis is on the relative contribution of the tropical and midlatitude forcings in governing the contrasting June rainfall during June 2013/14. There are evidences in the literature that tropical forcing can modulate the extratropical atmosphere (e.g., Krishnan *et al.*, 1998), which in turn affects the tropical atmosphere. Additionally, the extratropical weather systems can influence the tropical atmosphere on their own. Assessing the relative role of these forcings require experiments using idealized models and this is beyond the scope of the present study.

The skill of a CFSv2 based MME is also examined in predicting the observed discrepancy in June rainfall, on extended range. It is found that MME has remarkable skill in predicting June extremes and it could predict the contrasting behavior during June 2013/2014 in almost all pentad (P1-P4) leads. It not only predicted the observed difference in rainfall and wind circulation anomalies over the Indian region (**Figure 8**), but also reasonably predicted the

influential role of large scale meteorological conditions such as the El-Niño/La-Niña over equatorial Pacific, the TT gradients and the midlatitude influence, on the events (**Figures 10-12**).

The experimental extended range forecasts generated by IITM were disseminated at the IITM website since 2013, and these were used by IMD for generating agrometeorological advisory bulletins during 2013 and 2014 ISMs. These bulletins proved to be very useful to the farmers in planning agricultural operations well in advance by decreasing the vulnerability of agriculture to increasing climatic variability and thus increase the crop production during 2014, without putting additional stress on natural environment and also to manage the cost of cultivation (IMD, 2014). On the other hand, the reduced monsoon activity during June 2009 resulted in the rice and other *kharif* crop loss was significant with rice production declining by 20.7 million tons from the previous year's levels (source: Gain report of USDA Foreign Agricultural Service available at <http://www.tropmet.res.in/~kolli/MOL/Links/agri-impact.pdf>). If these forecasts were available during 2009 monsoon season, the advisories would have been given to the farmers in the right time and hence the crop loss would have been reduced to some extent. This study thus advocates the usefulness and suitability of the MME based on CFSv2 in the prediction of ISM variability on extended range and applications in agricultural planning.

Acknowledgements

IITM is fully supported by the Ministry of Earth Sciences, Govt. of India. The authors gratefully acknowledge the reviewers for their constructive and insightful comments that helped considerably in improving the manuscript. The model runs are carried out on Prithvi IBM High

Performance Computing System installed at IITM, Pune. The figures in this paper are generated using GrADS and Xmgrace.

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Table 1: Observed June rainfall in mm and its % departure from long term mean. Years with excess (deficit) June rainfall are marked in bold (bold + italics) font. The onset date, the date on which the ISM covered the whole country and the total number of days taken for the same are also given in the table.

Year	June Rainfall (mm)	Departure from Mean in %	MOK Date	Date of covering the entire country	Total Days taken to cover the country
2001	219.0	35.6	23 May	24 June	32
2002	180.1	9.4	29 May	15 August	66
2003	179.9	9.8	08 June	05 July	28
2004	158.7	-0.8	18 May	18 July	62
2005	143.2	-9.5	05 June	30 June	26
2006	141.8	-12.7	26 May	24 July	60
2007	192.5	18.5	28 May	04 July	38
2008	202.0	24.3	31 May	10 July	41
2009	85.7	-47.2	23 May	03 July	42
2010	138.1	-15.6	31 May	06 July	37
2011	183.5	12.2	29 May	09 July	42
2012	117.8	-28.0	05 June	11 July	37

2013	219.8	34.4	01 June	16 June	16
2014	92.4	-43.5	06 June	17 July	42

Figure Captions

Figure 1: (a) Rainfall anomaly (mm day^{-1}) and (b) 850hPa anomalous wind (m s^{-1} ; *streamlines*) and the KE ($\text{m}^2 \text{s}^{-2}$; *shaded*) of its rotational component, during June 2013. (c) and (d) are same as (a) and (b), but for 2014.

Figure 2: Time - height evolution of anomalous omega (pressure vertical velocity in hPa s^{-1} multiplied by -1.0; *shaded*) over Central India ($70^\circ\text{-}85^\circ\text{E}$; $15^\circ\text{-}25^\circ\text{N}$) during (a) 2013 and (b) 2014. (c) and (d) show the monsoon Hadley circulation anomalies during June 2013 and 2014 respectively. To construct the meridional circulation anomalies, the meridional and vertical velocities are averaged over the longitudes $70^\circ\text{-}90^\circ\text{E}$. The shading represents omega (hPa s^{-1}) anomalies taken with a negative sign.

Figure 3: (a) Moist Static Energy (MSE; kJ kg^{-1}) anomalies and (b) vertically integrated (surface to 500hPa) moisture (mm day^{-1}) anomalies, during June 2013. (c) and (d) are same as (a) and (b), but for 2014.

Figure 4: Sea surface temperature (unit: $^\circ\text{C}$) anomalies during June (a) 2013 and (b) 2014. Velocity potential ($\times 10^{-5} \text{m}^2 \text{s}^{-1}$; *shaded*) and divergent wind anomalies (ms^{-1} ; *vector*) at 200 hPa during June (c) 2013 and (d) 2014. Longitude-height cross-sections depicting the east-west (Walker) circulation anomalies over Indo-Pacific region during June (e) 2013 and (f) 2014. For constructing the east-west circulation anomalies, the zonal and vertical

velocities are averaged over the latitudes (5°S -5°N). The shading represents omega (hPa s^{-1}) anomalies taken with a negative sign.

Figure 5: Time evolution of north-south TT gradient (K) during 2013 and 2014.

Figure 6: 200 hPa zonal wind (m s^{-1} ; *vector*) during June 2013 and 2014. Magnitude of wind is *shaded* in the figure. Figures (a) and (d) corresponds to the period 01-10 June, whereas (b) and (e) represents 11-20 June; and (c) and (f) stands for 21-30 June.

Figure 7: Pentad-wise percentage departure of rainfall over monsoon zone (defined by Rajeevan et al. 2010) for observation as well as pentad 1 to pentad 4 (P1-P4) lead times.

Figure 8: (a) to (d) same as Figure 1(a), (e) to (h) same as Figure 1(c), (i) to (l) same as Figure 1(b), and (m) to (p) same as Figure 1(d); but for P1 to P4 leads of MME.

Figure 9: (a) to (d) same as Figure 2(a), (e) to (h) same as Figure 2(b), (i) to (l) same as Figure 2(c), and (m) to (p) same as Figure 2(d); but for P1 to P4 leads of MME.

Figure 10: (a) to (d) same as Figure 4(c), (e) to (h) same as Figure 4(d), (i) to (l) same as *top* panel of Figure 4e and (m) to (p) same as *bottom* panel of Figure 4f; but for P1 to P4 leads of MME.

Figure 11: Same as Figure 5, but for P1 to P4 leads of MME.

Figure 12: Same as Figure 6, but for P1 to P4 leads of MME. Here, (a)-(f), (g)-(l), (m)-(r) and (s)-(x) are for P1, P2, P3 and P4 lead times respectively.

Supplementary Figures

Suppl. Figure S1: Same as Figure 4 (a) and (b), but for 2001 and 2009.

Suppl. Figure S2: TT anomaly (K) during (a) June 2013, (b) June 2014, (c) January to May 2013 and (d) January to May 2014.

Suppl. Figure S3: Same as Figure 5, but for 2001 and 2009.

Suppl. Figure S4: (a)-(d) is same as Suppl. Figure S1(a), whereas (e)-(f) is same as Suppl. Figure S1(b).

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Figure 1: (a) Rainfall anomaly (mm day^{-1}) and (b) 850hPa anomalous wind (m s^{-1} ; *streamlines*) and the KE ($\text{m}^2 \text{s}^{-2}$; *shaded*) of its rotational component, during June 2013. (c) and (d) are same as (a) and (b), but for 2014.

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Figure 6: 200 hPa zonal wind (m s^{-1} ; *vector*) during June 2013 and 2014. Magnitude of wind is *shaded* in the figure. Figures (a) and (d) corresponds to the period 01-10 June, whereas (b) and (e) represents 11-20 June; and (c) and (f) stands for 21-30 June.

Figure 7: Pentad-wise percentage departure of rainfall over monsoon zone (defined by Rajeevan et al. 2010) for observation as well as pentad 1 to pentad 4 (P1-P4) lead times.

Figure 8: (a) to (d) same as Figure 1(a), (e) to (h) same as Figure 1(c), (i) to (l) same as Figure 1(b), and (m) to (p) same as Figure 1(d); but for P1 to P4 leads of MME.

Figure 9: (a) to (d) same as Figure 2(a), (e) to (h) same as Figure 2(b), (i) to (l) same as Figure 2(c), and (m) to (p) same as Figure 2(d); but for P1 to P4 leads of MME.

Figure 10: (a) to (d) same as Figure 4(c), (e) to (h) same as Figure 4(d), (i) to (l) same as *top* panel of Figure 4e and (m) to (p) same as *bottom* panel of Figure 4f; but for P1 to P4 leads of MME.

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Figure11: Same as Figure 5, but for P1 to P4 leads of MME.

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Figure 12: Same as Figure 6, but for P1 to P4 leads of MME. Here, (a)-(f), (g)-(l), (m)-(r) and (s)-(x) are for P1, P2, P3 and P4 lead times respectively.

Suppl. Figure S1: Same as Figure 4 (a) and (b), but for 2001 and 2009.

Suppl. Figure S2: TT anomaly (K) during (a) June 2013, (b) June 2014, (c) January to May 2013 and (d) January to May 2014.

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Suppl. Figure S3: Same as Figure 5, but for 2001 and 2009.

Suppl. Figure S4: (a)-(d) is same as Suppl. Figure S2(a), whereas (e)-(f) is same as Suppl. Figure S2b).

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Title:

Extremes in June rainfall during the Indian summer monsoons of 2013 and 2014: observational analysis and extended-range prediction

Date:

2016-04-01

Citation:

Joseph, S., Sahai, A. K., Chattopadhyay, R., Sharmila, S., Abhilash, S., Rajeevan, M., Mandal, R., Dey, A., Borah, N. & Phani, R. (2016). Extremes in June rainfall during the Indian summer monsoons of 2013 and 2014: observational analysis and extended-range prediction. QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY, 142 (696), pp.1276-1289. <https://doi.org/10.1002/qj.2730>.

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