**,Indian summer monsoon sub-seasonal low-level circulation predictability and
its association with rainfall in a coupled model**

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Abstract

This study investigates predictability of the sub-seasonal Indian summer monsoon (ISM) circulation and its relation with rainfall variations in the coupled model National Centers for Environmental Prediction (NCEP) Climate Forecast System version 2 (CFSv2). Hindcasts based on CFSv2 for the period of 1982 to 2009 are used for detailed analysis. Though the model is capable of predicting the seasonal ISM rainfall at long lead months, the predication skill of the model for sub-seasonal rainfall in general is poor for short and long lead except for September. Rainfall over the ISM region/Indian Subcontinent is highly correlated with the Low Level Jet (LLJ) or Somali Jet both in the observations and the model. The model displays improved skill in predicting LLJ as compared to precipitation in seasonal mean and September, whereas the model skill is poor for June and August. Detailed analysis reveals that the model LLJ variations throughout the season are overdependent on the El Niño-Southern Oscillation (ENSO) unlike in the observations. This is mainly responsible for the model's low skill in predicting LLJ especially in July and August, which is the primary cause for the poor rainfall skill. Though LLJ is weak in September, the model skill is reasonably good because of its ENSO dependency both in model and the observations and which is contributed to the seasonal mean skill. Thus in order to improve the skill of seasonal mean monsoon forecast, it is essential to improve the skill of individual months/sub-seasonal circulation and rainfall skill.

Keywords: Low-Level Jet, Predictability, Rainfall, Indian summer monsoon, ENSO

1. Introduction

Lower tropospheric circulation over the north Indian Ocean associated with Indian summer monsoon (ISM) has strong impact on rainfall over the Indian subcontinent (e.g., Joseph and Raman 1966; Findlater 1969a,b; Cherchi et al. 2007; Terray et al. 2005). Low Level Jet (LLJ) formation is associated with large thermal gradients between the Asian landmass and surrounding oceans and Coriolis force with peak strength at 850 hPa over the Arabian Sea (AS) (Hoskins and Rodwell 1995; Boos and Emanuel 2009). This LLJ with strong cross equatorial flow from the southern to northern Indian Ocean is the integral part of ISM system (Krishnamurti et al. 1976). Development of monsoon lows, depressions and convective rainfall over the monsoon region are related with barotropic instability of zonal flow associated with LLJ. This LLJ plays a very important role in transporting the moisture from the southern Indian Ocean to Indian subcontinent, and is crucial component for ISM rainfall.

Fluctuations in the LLJ determine the onset of southwest monsoon (e.g., Joseph et al. 2006; Krishnamurthy and Kinter 2003; Wang et al. 2009) and LLJ exhibits large intraseasonal and interannual variability (e.g., Joseph and Sijikumar 2004; Chowdary et al. 2006; Bhanukumar et al. 2010; Joseph et al. 2013). During developing El Niño years, reduced strength of LLJ in most of summer months is reported in literature (Webster et al. 1998; Kripalani and Kulkarni 1999; Bosch et al. 2011; Chowdary et al. 2014b). Further, variations in the Mascarene High could influence the cross equatorial flow and the strength of LLJ (e.g., Krishnamurti et al. 1976). On the interannual time scale, LLJ and ISM rainfall are significantly correlated (e.g., Wang et al. 2001; Joseph et al. 2013), suggesting the importance of relationship between lower tropospheric circulation and rainfall over the ISM region.

Many global climate models such as the recent Coupled Model Intercomparison Project phase 5 (CMIP5) models are able to represent the strength and location of LLJ well (e.g., Sayantani et al. 2015). Mitra et al. (2005) showed that Coupled General Circulation Models (CGCMs) are

able to predict LLJ location and strength reasonably well at long lead months during summer 2002. Terray et al. (2005) discussed the variations of LLJ and ISM rainfall associated with El Niño and Southern Oscillation (ENSO) in a coupled model. Kim et al. (2012) suggested that European Centre for Medium-Range Weather Forecasts (ECMWF) System 4 models have slightly overestimated the strength of Somali Jet (or LLJ). It has been demonstrated that regional/global climate models have better skills in predicting/simulating the ISM circulation variability (e.g., Chowdary et al. 2014a; Raju et al. 2014). Many models have better skill in predicting ISM dynamical indices as compared to rainfall indices (Chowdary et al. 2014a; Bandgar et al. 2014; Chaudhari et al. 2015).

Walker et al. (2015) have demonstrated that the monsoon circulation rather than the moisture dominates interannual variability of ISM. This suggests the importance of understanding and predicting the variability of ISM circulation and its relation with rainfall. A dynamic index (Wang et al. 2001), which is the difference of the 850-hPa zonal winds between a southern region of 5°N–15°N, 40°E–80°E and a northern region of 20°N–30°N, 70°E–90°E, determines the strength of LLJ. Thus this index is appropriate to examine the predictability of LLJ or monsoon or low level circulation interannual skills in dynamical forecasting models. This wind based index is better correlated with all ISM rainfall compared to other indices (e.g., Goswami et al. 1999). Further most importantly this study is focused on sub-seasonal/monthly prediction skill of ISM circulation along with seasonal mean in the National Centers for Environmental Prediction Climate Forecast System Version 2 (NCEP CFSv2; Saha et al. 2014), which is not studied systematically earlier.

The paper is organized as follows. Section 2 outlines the details of different data sets and model used in the study. Section 3 describes representation of ISM circulation and rainfall in the model. Section 4 discusses predictability of ISM circulation in sub-seasonal time scale. The summary is provided in section 5.

2. Model and data

The hindcast data product from NCEP CFSv2 (<http://cfs.ncep.noaa.gov>) is used, which is a state-of-the-art coupled dynamical climate forecast system (Saha et al. 2014). Atmospheric component of coupled model is NCEP Global Forecast System (GFS) with horizontal resolution of T126 and 64 hybrid vertical levels. The Geophysical Fluid Dynamics Laboratory Modular Ocean Model, version 4p0 (Griffies et al. 2004) is the ocean component of the coupled model. In this study, ensemble (9 member) data sets for the period 1982–2009 (28 years) are used. As the focus of this study is on boreal summer season (June through September; JJAS), lead forecasts issued from the months February, March, April, and May are named as lead-4, lead-3, lead-2, and lead-1 respectively for the seasonal ISM forecast. More detailed procedure related to CFSv2 hindcast data is provided in previous studies (e.g., Saha et al. 2014).

The Center for Climate Prediction merged analysis for precipitation (CMAP; Xie and Arkin, 1997), the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Data for sea surface temperature (SST) version 2 (OISST; Reynolds et al. 2002) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (ERA-Interim; Dee et al. 2011) data are utilized in the study. Monthly means of selected variables such as sea level pressure (SLP) and surface winds are obtained from ERA-Interim reanalysis. Correlation/Regression and time series analysis are carried out in the present study. Data is de-trended in order to remove any secular warming trend. Pronounced intra-seasonal variability is removed over the Indo-western Pacific Oceans by applying 3-month running average on all data over the study period of 1982-2009.

3. Mean monsoon circulation and rainfall

CFSv2 one-month lead (with May Initial conditions (ICs) precipitation and 850hPa winds climatology for JJAS (mean of June to September) and for individual months are illustrated in Fig. 1. During JJAS, CFSv2 shows higher rainfall over the oceanic region and low rainfall over the

Indian subcontinent (Figs. 1a and 1f). Though CFSv2 LLJ is stronger than observed over the AS, it is weaker over the southern peninsular India. This suggests that negative bias in precipitation over the Indian subcontinent can be partly attributed to poor representation of LLJ in east of 70°E. Similar to JJAS, June precipitation is higher over the oceanic region compared to land region in CFSv2 (Fig. 1g). Southwesterly winds associated with LLJ are extended to central India by July and persist in August as shown in the observations (Figs. 1c and 1d). Sperber and Palmer (1994) demonstrated that the development of LLJ and associated convergence enhances the precipitation over the southern peninsular India and on the other hand, over the north-western and central India stronger westerly flow suppresses dry-air advection and contributes to the increased precipitation. However, such westerly flow over the western and central India is weaker in the model during July and August compared to the observations (Figs. 1h and 1i). This further supports the relation between ISM rainfall over India and sub-seasonal variations in LLJ strength. During September, precipitation intensity and strength of LLJ are higher over ISM region in CFSv2 as compared to the observations (Figs. 1f and 1j). During summer months LLJ connects the Mascarene High in the southern hemisphere and the monsoon trough and transports moisture from the southern Indian Ocean to the Indian sub-continent. The variation in LLJ leads to changes in the moisture transport and results in the variations of ISM rainfall. Therefore, it is important to examine the predictability of LLJ variations during the monsoon months at sub-seasonal scale.

Time series of the ISM low level circulation index (IMCI) defined by Wang et al. (2001) for CFSv2 one-month lead and the observations during all summer months is shown in Fig. 2. Wang et al. (2001) demonstrated that the IMCI has good coherence with rainfall anomalies averaged over an extended region including the Bay of Bengal (BOB), Indian subcontinent and the eastern AS and it is also highly correlated with the all-India summer rainfall (e.g., Parthasarathy et al. 1992). Further, Wang et al. (2001) suggests that IMCI index reflects both the intensity of the monsoon westerly anomalies and the lower-tropospheric vorticity anomalies associated with the ISM trough and

represent the dominant modes of interannual variations of the ISM. Positive and negative peaks in IMCI/LLJ are apparent in JJAS and individual months during the period of 1982-2009 in both the model (1-month lead) and observations. Standard deviation of IMCI index suggests (provided at top of the plot) the clear existence of interannual variability in low level winds. This motivated us to examine the relation between rainfall over the Indian land region and LLJ variations.

Correlation between IMCI/LLJ and rainfall anomalies over central India in both observations and model for JJAS, and individual months June, July, August and September is illustrated in Fig. 3. The precipitation index over Central India (known as monsoon core index) is computed based on Rajeevan et al. (2010). Correlation is above 0.8 at 99% confidence level for the observations and model in the 1 to 4 month lead prediction. Observations show weak correlation in June and August compared to seasonal mean. The model shows strong relationship between circulation and rainfall even at long lead months. Over all, the model is able to represent the spatial distribution of low level circulation and rainfall over the ISM region for seasonal mean and individual months during summer season as compared to the observations. These results indicate that there is strong relation between LLJ and rainfall over India at interannual time scale in both the observations and model at different lead months. As the low level circulation has strong influence on rainfall, it is essential to measure the skill of the model in predicting the rainfall and circulation.

4. Predictability of circulation and rainfall

Model skills in predicating central India or monsoon core rainfall at different lead months are shown in Fig. 4a. Model displays some significant (0.32 at 90% confidence level) skill only at 3-month lead (initialized with March ICs) for JJAS rainfall. Similarly, June rainfall skill is better when initialized with March initial conditions. Model skill in predicting July rainfall decreases with increasing lead months (of 1 to 3 months) and slightly increases at 4 month lead but skill is not significant in any lead month predication. Model has no skill in predicating August rainfall over the central India, the skill is close to zero or negative for short to long lead month. September rainfall

skill of the model is significantly higher than seasonal mean and other individual months. Over all, model shows poor skill in predicting rainfall most of summer months (except September) for shorter or longer lead months.

In case of LLJ/IMCI index, model showed better prediction skill (Fig. 4b) for seasonal mean (JJAS) at all lead months (slightly low in 2 month lead). During June, model skill in predicting LLJ is positive and significant only at 3-month lead. Model skill is also significant for July LLJ at 2 and 3-month lead forecast. But during August, model skill is the least at all lead months for LLJ and that has reflected in the rainfall skill as well (Figs. 4a and 4b). September LLJ is better predictable in all lead months. However, this analysis demonstrates that model skill in predicating LLJ variability is better than rainfall predication over India except in August. This raises an important question that despite having strong relation between LLJ and ISM rainfall, why the model skill for LLJ is not translated for rainfall and why LLJ prediction skills are different in different months in the model. We have carried out further analysis to address these questions.

Figs. 5a-5d display observed correlation of IMCI index with SST and regressed upon 850hPa wind anomalies over the Indo-Pacific Ocean in both seasonal and sub-seasonal scales. It is found from the observations that seasonal (JJAS) mean and September SSTs over the central eastern Pacific are highly correlated with IMCI index. This clearly indicates that ENSO forcing in September is strongly influencing the monsoon circulation compared to other months, and so ENSO may be the major contributor for the skill in seasonal mean. Too strong teleconnections between seasonal mean ISM rainfall and ENSO in the model is consistent in earlier studies (e.g., Ramu et al. 2016; Saha et al. 2016). Strong easterly wind anomalies are apparent over the central and eastern Pacific in JJAS and September when regressed with IMCI index and are associated with ENSO. Western Indian Ocean SST and north Pacific SST are also well correlated with IMCI index particularly in June. Central/eastern Pacific SSTs are not well correlated with LLJ variations (Figs. 5c and 5d) in July and August. In particular, easterly wind anomalies are absent in August

and weak in July. Interannual variability of monsoon circulation may not be entirely forced by slowly varying boundary conditions but is also governed by internal dynamics as indicated by Goswami (1998). Unlike in the observations, CFSv2 at one-month lead showed strong correlation between IMCI index and SST over the central and eastern Pacific in all summer months including seasonal mean (Figs. 5f-5j). Strong SST signals are also seen over the western Pacific and Indian Ocean corresponding to changes in LLJ in most of the season. Anomalous easterly wind anomalies are seen throughout the season in CFSv2, which are associated with changes in the ISM circulation. We have used broad index based on the zonal wind averaged over large region (15°S to 10°N and 37.5°E to 62.5°E), which represents the strength of low level jet over the western Arabian Sea (Lin et al. 2008) and carried out analysis. Both IMCI index and broad index show similar results that the model ISM circulation variations are highly tied with ENSO (see Figure below). Further our examination with Krishnamurti et al. (1981) index (zonal wind averaged over 5°S – 20°N ; 50°E – 70°E) also suggests similar results. This analysis demonstrates that the model ISM circulation changes in the interannual time scale are over depending on ENSO. Thus, unlike in the observations strong association between ISM and ENSO in the model is mainly responsible for weak skill in predicting the monsoon circulation especially in August.

It is noted that observed rainfall over India and maritime-continent displayed positive correlation with IMCI index during JJAS (Fig. 6a). On other hand, central equatorial Pacific displays negative correlation suggesting the remote influence of the Pacific on monsoon circulation. However, in the sub-seasonal point of view, ISM rainfall is highly correlated with IMCI index during July and September, whereas the correlation is weak for June and August consistent with Fig. 3. Negative correlation between IMCI and rainfall over Pacific is apparent only in September (and in June) in observations similar to IMCI and Pacific SST. This suggests that monsoon circulation is influenced by remote forcing from Pacific mainly in June and September. Associated with the changes in IMCI index strong cyclonic circulation over the Indian landmass

during JJAS is noted (Fig. 5), which is favourable for enhanced rainfall (Fig. 6). Signals are weak over the central and eastern Pacific SLP when correlated with IMCI index in the observations in most of the season. In case of the model, the central and eastern Pacific rainfall and SLP are highly correlated with IMCI index, supporting the fact that the ISM circulation is over dependent on ENSO throughout the season (Figs. 6f-6j). Over all, unrealistic dependency of monsoon circulation to ENSO in models may lead to low prediction skill for ISM circulation and rainfall.

Apart from ENSO, another major ocean-atmospheric phenomenon called Indian Ocean Dipole (IOD, Saji et al. 1999) mode is known to influence the ISM circulation and rainfall (e.g., Ashok et al. 2001). Correlation of IMCI index with SST anomalies showed strong gradients over the tropical Indian Ocean region in the model unlike in the observations (Figs. 5f, 5i and 5j), which is also reflected in rainfall patterns (Figs. 6f, 6i and 6j). This motivated us to examine the relation between IOD and ISMR in the model. It is noted from the observations that during summer season IOD is positively (marginally) correlated with rainfall over some parts of India (Fig. 7a). But the model displays strong negative correlation of rainfall when correlated with IOD index during JJAS and in August. This clearly suggests that in the model IOD and ISM rainfall teleconnection is very poorly predicted/represented in the model. This might also undermine skill of the model in predicting ISM rainfall on the interannual time scale.

Similar analysis is carried out for model long lead month predictions. Figure 8 shows the correlation (regression) of IMCI index with SST (850 hPa winds) at 3 and 4-month lead model prediction. Similar to 1-month lead IMCI index is highly correlated with the central and eastern equatorial Pacific SST anomalies in summer months and for seasonal mean. Strong easterly wind anomalies over the ENSO region are apparent in the model long lead months when regressed with IMCI index. Further precipitation (SLP) anomalies showed significant negative (positive) correlation in the east of date line around the equator (Fig. 9). This strongly suggests that for short and long lead, the model ISM circulation is over dependent on the ENSO unlike in the

observations. Further IOD teleconnections also would influence the model skill in predicting ISM rainfall on the interannual time scale.

5. Summary

The present study investigates the relationship between sub-seasonal low level circulation and rainfall over the ISM region and their predictability during the period of 1982-2009 in the observations and NCEP CFSv2 model at different lead. We have used ERA-Interim reanalysis 850hPa winds and SLP, OISST and CMAP rainfall to compare with CFSv2 hindcast data. Strong relationship between low level wind circulation and rainfall during the ISM period is noted in both the observations and model. The model is able to represent the spatial distribution of low level circulation and rainfall over the ISM region for seasonal mean and individual months reasonably well during summer season as compared to the observations.

It is also noted that the model displays poor skill in predicting the central Indian rainfall in the seasonal and sub-seasonal time scales except in September. LLJ prediction skill in the model is better than precipitation at different lead except in August. On the other hand, correlation between rainfall over India and LLJ at sub-seasonal scale and seasonal mean is high in both the observations and the model. A couple of questions addressed here are (1) why prediction skill of LLJ is not translated for rainfall in the model despite having strong relation between them?, and (2) what is the reason for the low prediction skill for LLJ especially in August?

Analysis suggests that variation in monsoon low level circulation in the model is over dependent on ENSO in all four months and the seasonal mean. Therefore prediction skill of monsoon circulation in model is depending on the ENSO unlike in the observations. This unrealistic dependency of monsoon circulation on ENSO is primarily responsible for the low prediction skill of ISM rainfall in the model. Since ENSO is known to influence ISM circulation through changes in Walker circulation, it can alter the amount of rainfall received over the Indian subcontinent. As there is strong relation between circulation or LLJ and rainfall over India, any

unrealistic changes in model ISM circulation could influence the rainfall prediction skill. Further during August the relation between LLJ variations and ENSO is very poor in the observations, where as relation is significantly high in the model. This discrepancy in the model caused for poor prediction skill of LLJ during August. Further, IOD teleconnections with ISM rainfall and circulation in the model are poorly represented. Even at long lead, strong correlation between IMCI and central Pacific SST is evident. Correlation is slightly higher at long lead than in one month lead for seasonal mean and individual months. This is clearly suggesting that LLJ variability is strongly associated with ENSO in the model than in the observations. Thus present study suggests that improving the model skill of monsoon circulation may provide fair chance of enhanced skill for precipitation on seasonal and sub-seasonal time scales. Recent regional climate model experiments showed that the ISM circulation could be improved by simply improving tropospheric temperature gradients (e.g., Raju et al. 2014, 2015, 2017). Further studies are underway to look into the model physics, resolution and lower boundary conditions etc. as well as the other factors on which rainfall depends besides the ISM circulation.

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Figure captions

Figure 1. Climatology of observed 850hPa winds (vectors, m/s), magnitude (contours, m/s) and precipitation (shaded, mm/day) for (a) JJAS, (b) June, (c) July, (d) August and (e) September. Right panels from (f)-(j) are similar to (a)-(e) but for CFSv2 initialized with May ICs.

Figure 2. Low level circulation (m/s) or IMCI index (area average of zonal wind at 850hPa difference between 40°E - 80°E to 5°N - 15°N and 70°E - 90°E to 20°N - 30°N) for observations and CFSv2 (initialized with May ICs) for (a) JJAS, (b) June, (c) July, (d) August and (e) September for the period of 1982-2009.

Figure 3. Correlation between IMCI index and rainfall based on monsoon core index (area average for 18°N - 28°N to 65°E - 88°E) for JJAS, June, July, August and September for the observations and model at short to long lead month predications. Black line indicates correlation significant at 90% confidence level.

Figure 4. (a) Correlation of rainfall over the monsoon core index between observations and models at different lead month predictions for JJAS, June, July, August and September. (b) is same as in (a) but for IMCI (monsoon circulation) index. Black line indicates correlation significant at 90% confidence level.

Figure 5. Correlation of IMCI (LLJ) index with SST (shaded), and regressed upon 850hPa wind (vectors, m/s) for (a) JJAS, (b) June, (c) July, (d) August and (e) September in observations (left panels). Right panels from (f)-(j) are similar to (a)-(e) but for CFSv2 initialized with May ICs.

Figure 6. Correlation of IMCI (LLJ) index with precipitation (shaded), and SLP (contours) for: (a) JJAS, (b) June, (c) July, (d) August and (e) September in observations (left panels). Right panels from (f)-(j) are similar to (a)-(e) but for CFSv2 initialized with May ICs.

Figure 7. Correlation of the Indian Ocean dipole (IOD) mode index with rainfall (shaded) for observations (a) JJAS and (c) August, and for CFSv2 initialized with May ICs (b) JJAS and (d) August. Contours represent values significant at 90% confidence level.

Figure 8. Correlation of IMCI (LLJ) index with SST (shaded), and regressed upon 850hPa wind (vectors, m/s) (a) JJAS, (b) June, (c) July, (d) August and (e) September for CFSv2 3-month lead prediction (with March ICs) (left panels). Right panels from (f)-(j) are similar to (a)-(e) but for CFSv2 4-month lead (with February ICs) predication.

Figure 9. Correlation of IMCI (LLJ) index with precipitation (shaded), and SLP (contours) (a) JJAS, (b) June, (c) July, (d) August and (e) September for CFSv2 3-month lead prediction (with March ICs) (left panels). Right panels from (f)-(j) are similar to (a)-(e) but for CFSv2 4-month lead (with February ICs) predication.

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