Indian summer monsoon prediction and simulation in CFSv2 coupled model

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Abstract

Using carefully designed coupled model experiments, we have demonstrated that the prediction skill of the all India summer monsoon rainfall (AISMR) in Climate Forecast System version 2 (CFSv2) model basically comes from the El-Niño Southern Oscillation-Monsoon teleconnection. On the other hand, contrary to observations, the Indian Ocean coupled dynamics do not have a crucial role in controlling the prediction skill of the AISMR in CFSv2. We show that the inadequate representation of the Indian Ocean coupled dynamics in CFSv2 is responsible for this dichotomy. Hence, the improvement of the Indian Ocean coupled dynamics is essential for further improvement of the AISMR prediction skill in CFSv2.

Keywords: Indian summer monsoon; seasonal prediction; ocean–atmosphere coupled dynamics; CFSv2; coupled model; ENSO-monsoon teleconnection

1. Introduction

Early and accurate seasonal prediction of Indian summer monsoon (ISM) during June through September (JJAS) is very important for proper planning and the socioeconomic well-being of India as majority of people in this region depend on rain-fed agriculture for their life and existence. Recently, Gadgil and Srinivasan (2011) have studied the simulation of the all India summer monsoon rainfall (AISMR) in five atmospheric general circulation models (AGCMs) and they have shown that the poor prediction skill in many AGCMs arise due to excessive teleconnection with El-Niño Southern Oscillation (ENSO). Tropical Ocean Global Atmosphere (TOGA), Global Ocean Global Atmosphere, Seasonal Prediction of Indian Monsoon (SPIM) and similar experiments, mainly focus on the response of the atmosphere to the sea surface temperature (SST) forcing (Lau and Nath, 2000; Gadgil and Srinivasan, 2011) based on two-tier modeling strategies where the atmosphere and ocean are treated separately by using the AGCM, which is forced by either observed boundary condition or output from the ocean general circulation models. One of the important limitations of the two-tier experimental design is that in reality a part of the SST especially over the warm pool regions evolves in response to the atmospheric change (Lau and Nath, 2004; Wang et al., 2004; Yu and Lau, 2005).

Recent studies (Kumar et al., 2005; Rajeevan et al., 2012 and the references there in) have reported progress in the multi-model ensemble anomaly correlation coefficient (MME ACC) of AISMR, from 0.28 (DEMETER; Palmer et al., 2004) to 0.45 (ENSEMBLE; Hewitt, 2004) in ocean–atmosphere coupled general circulation models initialised with May initial condition for the period 1960–2005, but the potential predictability of AISMR in coupled models is yet to be achieved. It is important to understand how to further improve the AISMR prediction skill in coupled models. To address this, we have carried out a couple of sensitivity experiments using a state-of-the-art coupled model to quantify the relative importance of the Pacific and Indian Ocean coupled dynamics in modulating the interannual variability of the AISMR. In Section 2, we describe the model and experimental design along with observational datasets used in this study. Section 3 demonstrates the relative importance of the Pacific and Indian Ocean coupled dynamics in simulating the ISM. Section 4 summarizes the results.

2. Model and experiment design

To understand the relative role of active ocean dynamics of different basins in forcing the interannual variability of the ISM, we have carried out a set of sensitivity experiments along with control (CTL) run using CFSv2 coupled model. The National Centers for Environmental Prediction (NCEP) Climate Forecast System version 2 (CFSv2; Saha et al., 2014b) is a state-of-the-art coupled climate model developed by the NCEP, USA. The atmospheric component of the CFSv2 is Global Forecast System with a spectral resolution of T126 and 64 hybrid vertical levels and the ocean component is Geophysical Fluid Dynamics Laboratory Flexible Modeling System Modular Ocean Model version 4p0d. In addition, it has a four-layer NOAH land surface model and a three-layer dynamical sea ice model coupled together with the atmosphere and ocean components in Earth
System Modeling Framework. In this study, both CTL and sensitivity runs are made in hindcast mode (initialised every year) and integrated for 9 months lead time, for the period 1982–2009. Both CTL and sensitivity runs are an ensemble mean of five realizations of CFSv2 T126 model runs initialized with the February initial conditions (00z05Feb, 00z10Feb, 00z15Feb, 00z20Feb and 00z25Feb). The CFSv2 reanalysis (Saha et al., 2010) obtained from NCEP are used as the initial conditions for the model run.

The CTL run (same as original CFSv2) has ocean dynamics and ocean-atmospheric coupling all over the globe while in the Indian Ocean slab (ISLAB) run, active ocean dynamics are removed from the tropical Indian Ocean, instead a uniform slab (50 m) over the tropical Indian Ocean (30°S to 30°N; 45°E to 120°E) provides the flux-driven SST. We have carried out separate sensitivity experiments by prescribing Mixed Layer Depth (MLD) as 40, 50 and 60 m, but modest changes to this fixed MLD do not alter the major conclusions of this study. Hence, the results from those sensitivity experiments which have a uniform 50 m slab MLD are discussed in this study. Some of the earlier studies used prescribed climatological SST forcing to remove the influence of SST variations in some basin (Lau and Nath, 2004; Yu and Lau, 2005; Achuthavarier et al., 2012). There is another set of sensitivity studies (Yokoi et al., 2012) using prescribed climatological wind stress fluxes to the ocean in order to remove atmospheric coupling while keeping ocean dynamics. Both of the above-mentioned strategies use some kind of climatological forcing field into the coupled system. Hence, the ocean and atmosphere over the same basin exist in two different states (one is in climatological and the other is in dynamical state). This resembles the two-tier modeling strategy of standalone models. Spatial and temporal variations in the MLD [e.g. E2 experiment of Krishnan et al. (2011)] are not prescribed in the sensitivity experiment because it is a well-known fact that MLD variations are also partly due to coupled ocean-atmosphere dynamics. The coupled sensitivity experiment designed for this study uses a strategy by which the thermodynamical forcing is maintained while completely removing ocean dynamics in a particular basin (This indirectly removes the dynamical component of ocean-atmosphere coupling as well). The 50 m uniform regional slab ocean in this experiment resembles Tropical Ocean Global Atmosphere with Mixed Layer Ocean experiment (TOGA-ML) experiment of Lau and Nath (2000), Slab ocean experiment of Dommenget (2010) and E1 experiment of Krishnan et al. (2011), except for the differences in the domain. In ISLAB run, the atmosphere is coupled with fully dynamical Ocean elsewhere outside the tropical Indian Ocean. Hence, the difference between ISLAB and CTL runs isolates the role of Indian Ocean coupled dynamics. Similarly, the Pacific Ocean slab (PSLAB) run is identical to the ISLAB run except that coupled dynamics are removed only from the tropical Pacific Ocean (30°S to 30°N; 120°E to 75°W). Therefore, the comparison of the PSLAB run and CTL run isolates the role of Pacific Ocean coupled dynamics. As the model integration is for 9 months, we have not used any flux correction in any of the sensitivity experiments as model-simulated SST does not drift significantly.

In order to evaluate the model-simulated rainfall, we use the pentad precipitation from Global Precipitation Climatology Project (Xie et al., 2003). We use the monthly Extended Reconstructed SST version 3 (Smith et al., 2008) to verify the model-simulated SST.

3. Results and discussion

3.1. Model biases in simulating SST and precipitation

Figure 1(a) shows the seasonal mean SST in tropics, which clearly displays warm SSTs (>28 °C) over the Indo-Pacific region covering the eastern Arabian Sea, the entire Bay of Bengal, the eastern equatorial Indian Ocean and the western tropical Pacific, including the South Pacific Convergence Zone, coinciding with well-known warm pool regions. The CFSv2 CTL run is able to capture the observed large-scale spatial pattern of SST (figure not shown). However, it exhibits a cold SST bias over the entire Indian Ocean, northwest and southwest Pacific Ocean and a narrow region of cold bias over the central equatorial Pacific (Figure 1(c)). Warm SST bias over the south/north eastern tropical Pacific Ocean (Figure 1(c)) is also observed. Previous study by Pokhrel et al. (2012) argued that the cold SST bias over the Indian Ocean in CFSv2 CTL run is due to dry surface atmosphere and associated increase in the latent heat flux. Furthermore, we have noticed that the model (CTL run) overestimates the net heat loss (Unit: Peta Watt here after PW) from the northern Indian Ocean (observed ~0.61 PW; CTL run ~0.98 PW) and underestimates heat gain over the southern tropical Indian Ocean (observed 1.34 PW; CTL run ~0.30 PW). As a result, the model underestimates (cold bias) the SSTs over the Indian Ocean. Detailed analysis of the heat budget will be reported elsewhere. The warm SST bias over the north/south eastern Pacific may be a result of misrepresentation of stratus cloud decks in the eastern Pacific and the resulting penetration of more shortwave radiation to the surface, as reported by Zheng et al. (2011).

The seasonal mean precipitation over south Asian summer monsoon region show three zones of maximum rainfall, namely the head Bay of Bengal, the eastern equatorial Indian Ocean and the western coast of India (Figure 1(b)). The CFSv2 is able to capture these zones of maximum rainfall over ISM domain (Saha et al., 2014a). In spite of cold SST bias (Figure 1(c)), the model overestimates rainfall over oceanic regions (Figure 1(d)), probably due to the fact that the SSTs over these regions are still above the critical SST (27.5 °C) for convection to occur. Contrary to this, the rainfall
over land regions is underestimated (Figure 1(d)). The dry bias over the Indian land mass is not unique to the CFSv2 model, but many CMIP5 models have also shown a similar bias in the precipitation simulation (Sabeerali et al., 2013). Recent study by Saha et al. (2012) has reported that the dry bias over the Indian land region can be reduced by correcting the biases of Eurasian snow cover. In order to understand how coupled dynamics in each basin control model biases, two sensitivity experiments are carried out. The details of the sensitivity experiments are already described in Section 2. Here, we discuss results from these sensitivity experiments.

The CFSv2 ISLAB run, compared with CTL run, shows that absence of Indian Ocean dynamics results in colder (warmer) SST in the southern (northern) tropical Indian Ocean (Figure 1(e)), indicating the lack of southward heat transport. The cold SST bias over the equatorial central Pacific has increased in the ISLAB run (Figure 1(e)) and cold biases over the northwest and southwest Pacific remain unchanged (Figure 1(e)). These results indicate that the Indian Ocean coupled dynamics have a crucial role in determining the SSTs over the southern Indian Ocean and the equatorial central Pacific, whereas the Indian Ocean coupled dynamics have no significant role in deciding the SSTs over the northwest and southwest Pacific. In response to the reduced SST bias over the northern Indian Ocean, the dry bias over the Indian landmass has decreased in the ISLAB run (Figure 1(f)). By prescribing the slab in the Indian Ocean and calculating the SST simply from the net heat flux, it is clear that in the absence of active coupled dynamics, the SST in the northern tropical Indian Ocean exhibits slight warm bias (due to the absence of southward heat transport) in contrast to the cold bias (due to overestimation of southward heat transport) in the CTL run. This study confirms that the SSTs in the northern Indian Ocean are primarily determined by the surface heat fluxes, as suggested by Shenoi et al. (2002), whereas the realistic active coupled dynamics in the Indian Ocean are important in determining the correct SSTs over the southern Indian Ocean in CFSv2 because the southward (westward) heat transport through the northern (eastern) boundary dominantly determines the SSTs over southern tropical Indian Ocean. The SST–precipitation lead–lag relationship (Figure 2) in the warm pool regions (Bay of Bengal, Eastern Equatorial Indian Ocean and Northwest Pacific) are not captured in the model due to strong cold bias (up to −1°C). However, in ISLAB
Figure 2. Spatial map of lead–lag relationship between SST and precipitation at each grid point for observation (left panel), CFSv2 CTL run (middle panel) and ISLAB run (right panel). First row marked as lag $-20$ indicate that the SST lead 20 days before the precipitation peak and similarly bottom row marked lag 20 indicate the SST lag 20 days after the precipitation peak.
run, due to better simulation of SSTs in the warm pool regions, the lead–lag relationship of air–sea interaction is reasonably simulated.

In the absence of the Pacific Ocean coupled dynamics (Dommenget, 2010), the warm bias over the eastern equatorial Pacific Ocean has strengthened in magnitude and spatial extent (Figure 1(g)), which resembles a perennial El-Niño condition. This is due to the absence of upwelling along the coast of Peru and eastern equatorial Pacific in the PSLAB run. During an El-Niño event, the associated teleconnection forces a warming over the western Indian Ocean and Arabian Sea (Murtugudde and Busalacchi, 1999; Venzke et al., 2000). Similar warming associated with perennial El-Niño type bias is noticed in PSLAB run. Similarly, the strengthening of cold bias over the northwest and southwest Pacific Ocean (Figure 1(g)) is due to absence of the dynamics associated with subtropical gyre and western boundary current. The perennial El-Niño type bias in the PSLAB run further enhances the dry bias over the Indian land region and there exists a wet bias all along tropical oceans (Figure 1(h)). This response is due to the well-known ENSO–monsoon teleconnection relation, wherein El-Niño condition over the Pacific forces subsidence over the Indian land region (Rajeevan and Pai, 2007, and the references therein).

3.2. Teleconnections associated with AISMR

ENSO and IOD are the two dominant modes of climate variability over tropical oceans and the interannual variability of the AISMR is mainly related to these two modes (Kumar et al., 2006, and the references therein). The spatial pattern of correlation between the observed AISMR and global SST shows a negative correlation over the central/eastern tropical Pacific and major portions of the central/eastern Indian Ocean (Figure 3(a)), while positive correlation is observed over the western Pacific warm pool region and along the Somali–Oman coast (Figure 3(a)). The CFSv2 CTL run is able to capture this large-scale spatial pattern of observed correlation over the Pacific Ocean (Figure 3(b)). However, compared with observations the Pacific ENSO is strongly coupled to AISMR in CFSv2 CTL run (Figure 3(b)). As evident in Figure 3(a), several studies

Figure 3. Spatial map of seasonal (JJAS) SST correlated with AISMR index for (a) observation, (b) CFSv2 CTL run, (c) ISLAB run, (d) PSLAB run. Statistically significant values (95% confidence level) are contoured.
in recent times have highlighted that the central Pacific warming (El-Niño Modoki) is more conducive to force drought condition over India (Kumar et al., 2006) compared with eastern Pacific warming (canonical El-Niño). However, many coupled models failed to capture this relationship (Wang et al., 2015). CFSv2 also suffers from the same limitation by which strong negative correlation between AISM and SST is concentrated over the eastern Pacific. In contrast to observations, the CTL run shows positive correlations all over central/eastern Indian Ocean and a negative correlation along the monsoon wind track (Figure 3(b)). The positive correlation over the western Pacific warm pool region is very strong (Figure 3(b)) compared with observations. This suggests that in CFSv2, a negative dipole-like structure in the Indian Ocean and La-Niña-like condition in the tropical Pacific will enhance precipitation over India. On the other hand, in observations, a positive dipole-like structure and a La-Niña-like structure are associated with good monsoon condition. This indicates that in CFSv2 the monsoon teleconnections over the tropical Indian Ocean are exactly opposite to the observed teleconnection. This suggests that further improvement in AISM skill is possible by improving the simulation of Indian Ocean teleconnections.

In the ISLAB run, the teleconnection pattern over the Pacific Ocean is almost identical to the CTL run, although the influence of the eastern/central Pacific SST on the AISM has increased and the negative correlation has further extended to the western Pacific (Figure 3(c)). The extension of negative correlation to western Pacific is due to extension of easterlies into the western Pacific in ISLAB run (figure not shown). Contrary to the CTL run, strong negative correlations are noticed in the ISLAB run along the path of monsoon cross-equatorial flow (Figure 3(c)), which suggests that the strong monsoon strengthens the cross-equatorial flow, and thereby, enhancing the latent heat loss from the ocean and cooling SST along its path (Shukla and Misra, 1977).

However, in the PSLAB run, the teleconnection between the Indian Ocean SST and AISM is marginally improved compared with observations in the western tropical Indian Ocean wherein positive correlation between the western Indian Ocean SST and AISM is faithfully captured (Figure 3(d)). However, the negative correlation pattern over the central and eastern equatorial Indian Ocean is not captured (Figure 3(d)), demonstrating that central and eastern equatorial Indian Ocean coupled dynamics are not represented properly in PSLAB run also. In the absence of Pacific Ocean coupled dynamics in PSLAB run, teleconnections associated with ENSO have completely disappeared from the Pacific Ocean as expected (Figure 3(d)).

The CTL run reasonably captures the spatial patterns of SST (as well as rainfall) in the tropical Indian Ocean correlated with Niño 3.4 (figure not shown). These indicate that the ENSO teleconnections are reasonably captured in the model, while the AISM teleconnection with the Indian Ocean SSTs are misrepresented in the model.

3.3. Interannual variations of AISM

The evolution of the AISM over years (Figure 4) shows that the magnitude of rainfall is underestimated in the CFSv2 CTL run compared with observations. The magnitude of AISM in ISLAB run is comparable with observations (Figure 4). In contrast, in the PSLAB run, the magnitude of the AISM is exceptionally weak (Figure 4). This result could be interpreted in two different ways: (1) in the CTL run, Indian Ocean coupled dynamics are not simulated reasonably, hence the convection over the equatorial Indian Ocean is overestimated and resulted in subsidence over the Indian landmass through modulation of local Hadley cell; (2) in ISLAB run, the northern (southern) Indian Ocean exhibits warm (cold) bias, due to the absence of meridional heat transport and resulting in enhanced (suppressed) convection over the northern (southern) Indian Ocean. Both of the above interpretations suggest that proper representation of air–sea heat fluxes and ocean dynamics in the tropical Indian Ocean can improve the AISM simulation. In order to make better predictions, the ENSO–monsoon teleconnection and Indian Ocean SST–monsoon teleconnection should be better represented in the model. The CFSv2 T126L64 in general underestimates the interannual variance of

Figure 4. Interannual variations of Indian summer monsoon rainfall for different CFSv2 run and observation.
AISMR in all runs, particularly in ISLAB and PSLAB runs compared with observations. The observed inter-annual variance of the AISMR anomaly is about 0.36 mm$^2$ day$^{-2}$, while the same is 0.25 mm$^2$ day$^{-2}$ in CTL run. In ISLAB run, the interannual variance drops to 0.12 mm$^2$ day$^{-2}$ (50% of CTL), which suggests that 50% of interannual variance of AISMR in CFSv2 is related to the Indian Ocean dynamics. Similarly, in PSLAB run, the interannual variance drops to 0.06 mm$^2$ day$^{-2}$ (20% of CTL), indicating that 80% of AISMR variance in CFSv2 is related to the teleconnection from the Pacific Ocean dynamics. On the other hand, the root mean square error (RMSE) is maximum in the PSLAB run (0.7), while it is less for the CTL and ISLAB (0.5) run. ACC of AISMR drops significantly in the PSLAB run (0.14) compared with CTL (0.53) and ISLAB runs (0.51). Large RMSE and small ACC in the PSLAB run indicate that interannual variations and phase of the AISMR anomaly in CFSv2 are mainly driven by ENSO–monsoon teleconnections in the model. It should be noted that the Indian Ocean dynamics contribute significantly to the interannual variance of AISMR.

4. Summary

The CFSv2 model has a dry bias over Indian land region, while the misrepresentation of Indian Ocean dynamics leads to improper ocean–atmosphere interactions and overestimated oceanic rainfall coexisting with cold SST biases. Better simulation of ocean–atmosphere interactions and reduced dry bias over Indian land along with simulation of warmer SST in northern Indian Ocean in the ISLAB run confirms that the dry bias over the Indian landmass is primarily due to cold SST simulated in the tropical Indian Ocean. Similarly, significant drop in AISMR variance in ISLAB run suggests that ocean dynamics in the Indian Ocean are important for the proper simulation of the interannual variance of AISMR. The study reveals the relative importance of the Indian Ocean and Pacific Ocean coupled dynamics in determining the seasonal mean rainfall over the Indian land region and its hindcast skill. The major portion of the prediction skill of AISMR basically comes from the Pacific Ocean teleconnections, and it is reasonably captured in the CFSv2. These results suggest that the Indian Ocean SST bias should be minimized to reduce the seasonal mean dry bias over the Indian land region, whereas the Indian Ocean SST and AISMR teleconnections should be reasonably captured to improve the AISMR prediction skill. These findings highlight the need to improve the Indian Ocean coupled dynamics in CFSv2 for the further improvement of the prediction skill of AISMR. Even though this study is based on CFSv2 model, similar biases are reported in other models from leading climate centers and hence the findings from this study will be useful for addressing the biases in other models also.

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