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Reply to Referee 1 on the manuscript "Role of surface hydrology in determining the seasonal cycle of Indian summer monsoon in a general circulation model"

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First of all, authors thank the reviewer for fundamental comments on this study.

Comment: This study conducted 10-years simulation of AGCM equipped with CLM to represent precipitation distribution by Indian monsoon system, and try to reveal a role of soil moisture variability in the GCM to modify the summer monsoon onset. According to the comparison of precipitation amount and distribution between CNTL run and TRMM observation, overestimation over the GP was evident on June with positive soil moisture bias in India. According to sensitive studies by changing the soil moisture in different spatial scales, remote dry soil moisture biases over Western Central Asia induced the early monsoon onset in the GP. Combined effects with remote and local configuration of soil moisture could also improve the seasonal progress of Indian monsoon. Authors concluded that such GCM experiments could contribute for diagnose the function of soil moisture on the monsoon onset and improve the land surface models.

First of all, I would like to mention that reduction of the model bias by changing the boundary condition (such as soil moisture distribution) does not mean that such boundary condition play an important role for actual monsoon variability. This paper confuses those two issues that lead readers for misunderstanding that soil moisture in Western Central Asia play and important role for the monsoon onset in GP. Object of the paper may be limited to improve monsoon simulation in the GCM.

Reply: We strongly disagree with the reviewer. Firstly, the purpose of this study is NOT to illustrate that a prescribed field of boundary condition (such as soil moisture) in the model improves the simulated (interannual) variability of monsoon. Our manuscript neither does discuss interannual variation of model simulated results in its default format (CNTL) nor indicates any change in its interannual variations resulting from the perturbed simulations. Instead, we emphasise that both local and remote soil moisture biases simulated by the model contribute to distorted seasonal cycle of monsoon over GP. For that, we did a 10-year long simulation without year-to-year variation of SST, to eliminate the interannual variation arising from it.

We agree that our study shows the importance of soil moisture bias over Western Central Asia (WCA) on the early monsoon rainfall (possibly linked to onset of monsoon) over GP in this model. We would like to refer to a few recent studies showing the importance of climate over WCA on monsoon over India. Samson et al. (2016) shows the importance of prescribed albedo over WCA on annual cycle. However, in a model surface albedo is a function of soil moisture. And thus, our study both confirms the finding of Samson et al. (2016) and takes it a step ahead in the context of error in another climate model. Rai et al. (2015), using observations, have shown the importance of climate over WCA during April-May on the early monsoon rainfall over India. We have shown that error in land-surface model can introduce large error in the simulation of rainfall annual cycle. And thus our study hints at the need to improve surface processes in the CLM, especially over GP and WCA. And while combining these above findings, we feel that, once this bias is improved, it will help improve the interannual variation of monsoon in the model. However, this could be a scope of future study.

Comment: By means of weather and climate system, monsoon precipitation variability in GP area is induced by maritime onset vortex and monsoon lows with continental monsoon trough combined with orographic induced thermal/dynamic flows over Indian sub-continent. If those systems were not represented in the model, precipitation and associated soil moisture distribution are failed. However, the paper did not explain about the representation of precipitation disturbances in the model. For instance, I could not understand that how the anomaly pattern of low-level flow in Fig. 12 could change the precipitation systems. Does the simulation represent diurnal precipitation variability?

We understand the concern of the reviewer, that a poor representation of the oceanic systems such as lows would impact the rainfall, and subsequently soil moisture, over GP. Such systems are primarily concentrated during the monsoon season. We would like to refer to Figures 2c and 5 of our manuscript, where we show the annual cycle of rainfall over GP as well as soil moisture over GP and WCA. A careful comparison reveals that CNTL has positive (negative) soil moisture bias over GP (WCA) throughout the year. This is in spite of comparable amount of rainfall in CNTL to that observed in March–May over GP (Fig 2c). Thus, this bias in soil moisture during pre-monsoon season cannot be due to error in representing monsoon systems by the model. Similarly, a consistent dry bias over semi-arid region like WCA calls for further investigation of its cause in the model, including its land-surface scheme.

In accordance of this comment of the reviewer, however, we have looked at the skill of CNTL in representing intraseasonal variability of rainfall which are tightly associated with monsoon systems. Such analysis can best be done in frequency domain similar to that carried out by Karmakar et al. (2015). Two dominant characteristic time-scales of variability of Indian monsoon are the low frequency oscillations (on 20-60 days time-scale) and the high frequency oscillations (on 10-20 days time-scale). The model is able to capture the variability in both the modes reasonably. Following figure summarizes the percentage of the total daily variability explained by the low frequency and high frequency oscillations in TRMM estimation and CNTL simulations over GP. We plan to include a discussion on this in the revised manuscript.

Dai and Trenberth (2004) showed that CAM2 was able to capture the diurnal cycle of surface air temperature well, especially over land. But this model suffered from systematic bias in cloud fraction simulation. This deficiency was mainly linked to convective parameterization scheme. Yuan et al.(2013) showed that CAM5 was able to capture the diurnal cycle of precipitation over East Asia, with varying accuracy spatially. CAM5 simulated the diurnal variation of stratiform clouds better as compared to convective clouds. Moreover, the model was also able to capture the diurnal phase variations of low level winds. We have not looked into diurnal time-scales in this work, which focuses on biases in the monthly and seasonal means.

Comment: I agree that Indian monsoon sector is composed by large land-surface spatial inhomogeneity, such as vegetation, complex terrain and associated soil moisture heterogeneity (P3 upper), that could link to occurrence of individual precipitation systems. Also, diurnal forcing is obviously affecting the precipitation system in the coastal and mountain range areas. To

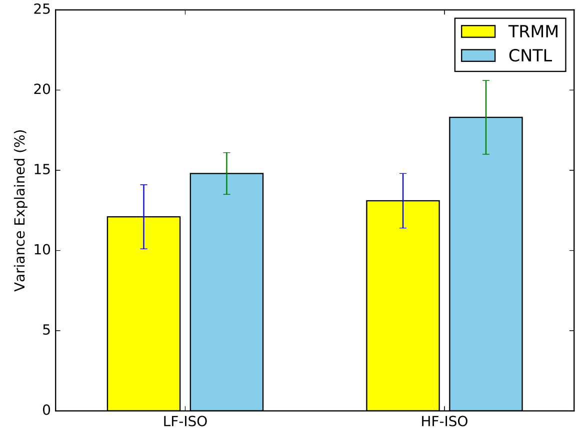

Figure 1. Contribution of the low-frequency intraseasonal oscillations (LF-ISO) and the high-frequency intraseasonal oscillations (HF-ISO) to the total daily variance of rainfall in June–September over Gangetic Plain. The error bars show one interannual standard deviation.

reveal the function of land-atmosphere interaction, non- hydrostatic models with dynamic downscaling simulation, that could explicitly tread the sub-grid scales functions, should be conducted. I understand that computation facility sometimes limits long-term downscaling simulations. However, this paper obviously indicated that GCM is hard to represent a reality associated with sub-grid scale hydrologic heterogeneity, because the CNTL had large biases. I doubt a scientific importance on diagnosing the role of soil moisture impacts by using GCM.

Reply: Please note that we have used a global climate model at a resolution that is reasonably high (about 0.5 degrees in longitude/latitude) to represent large scale heterogeneity in land surface and orography. Moreover, the land component of our model, CLM, has robust schemes to deal with sub-grid level heterogeneity. We have discussed this in Page 3, Line 28 (Section 2.1 of the manuscript) along with relevant references.

A non-hydrostatic model demands a resolution that is often impossible to run in climate mode (such as that in this study) even with fastest computers. Thus, use of such model would require a compromise to use it only over a specific region. We would like to point here out that such regional models, since forced at its lateral boundaries, are unable to consider atmospheric feedback arising out from remote locations. One example could be global scale change in upper tropospheric circulation due to regional forcing. These feedbacks become especially important in climate time scales. Therefore, we do not prefer to use a regional model to address the problem of this study.

Comment: Another problem is the setting of boundary condition in the sensitivity studies. GLDRY and GLWET runs are conducted with 1% and 100% soil water saturation, respectively. I am not sure how much they could correspond to volumetric water contents by means of in-situ soil structure, but they are definitely unrealistic. The paper set such extreme (idealized) conditions to explain the cause of biases between the CNTL products and actual statuses (observations).

Reply: Firstly, we would like to clarify the point relating soil water and volumetric water content. A 100% saturation (SAT runs) means filling the soil with its field capacity. This corresponds to $0.48\ mm^3/mm^3$ over GP region. Similarly, 1% saturation (DRY runs) corresponds to about $0.005\ mm^3/mm^3$ of water in volumetric units.

Secondly, regarding the unrealistic nature of these two simulations (GLDRY and GLWET), we agree that these are extreme cases. However, we have not used these two simulations to explain the cause of bias in CNTL. We have only used these two runs at the end of paper, in Figure 13, to show the sensitivity of simulated precipitation in model to soil moisture as boundary condition. These two runs set the extremes of sensitivity of model to soil moisture conditions. And it can be noted from Figure 13 that all other experiments fall between these two experiments.

Comment: By means of idealized simulation, changing of SST in certain areas may cause much impact on GP precipitation, because maritime disturbances have large impacts of northwestern Indian sub-continent climate.

Reply: We agree that changing SSTs in certain areas may have impact on GP precipitation. But the goal of this study is to analyse the effect of land-atmosphere coupling over GP. And this is best understood when SST variations do no influence the land-atmosphere interaction.

Minor comments

1. P3L7&L16 Is AGCM and CESM the same? Better to unify the term.

Reply: We have used the atmospheric component of CESM model in our study, which is referred as CAM in manuscript. We will replace the term "AGCM" appropriately to avoid confusion.

*2. P3L28 I could not understand the meaning of "nesting LCS4". You calculated the land- surface part within the 0.43*0.63 degree in GCM? Or you nested a certain region in GCM to drive LCS4 ?*

Reply: We have not used the term "nesting LCS4" anywhere in the manuscript. But clarification about "nested subgrid level hierarchy" in P3L28 is as follows: we have run the CLM model at a grid resolution of 0.43×0.63 degree which is same as that for its atmospheric counterpart. The phrase "nested subgrid level hierarchy" in description of CLM model refers the way in which sub-grid level heterogeneity is taken care of in the model.

3. Section 2.1 How much of the time step for calculation and time resolution of the output?

Reply: Section 2.1 is related to model description. We will add a line about time-step and output frequency in section 2.3-Experiment setup details in the beginning of section. This information was added under "Regionally Nudged Runs" - P5L6 and P5L13.

4. Section 2.2 Better to explain in details about the soil moisture products with reliability. Also, which years of the soil moistures to be used/compared?

Reply: ESACCI Soil moisture data for the period 2000-2010 has been used (P4L16). The manuscript includes references (Wagner et al., 2012; Liu et al., 2012) for details on ESACCI data product. It also includes a reference for ESACCI data validation carried out by Dorigo et al. (2015), using ground-based observations. We will add more details about the ESACCI data and its reliability in the manuscript.

5. Fig.1 Why you showed global scale distribution? In the global scale, there are many areas to be explained that CNTL and observations are different except in the Asian monsoon sector. Better to limit the discussion in a monsoon region, such as in Fig. 2.

Reply: We have shown Asia-Pacific monsoon region (Wang and LinHo, 2002) in Figure 1, (that is 15 S– 45 N, 40– 290 E). We wanted to highlight that model captures the spatial distribution of seasonal mean rainfall (Jun-Sep) reasonably well over Asia-Pacific monsoon system, with a spatial correlation of 0.76. This figure shows the large scale picture. We also show the monthly mean rainfall over Indian region to highlight the bias in precipitation in model over Indian region. Thereon we move towards the objective of this paper.

6. P6L15-25 June is a transitional month from pre-monsoon to monsoon. If the model output could produce daily base, why don't you assess the difference of seasonal progress between the CNTL and observation to identify the key monsoon flow anomaly affected by the differences in soil moisture distribution if any? P8L15-16 A sentence "onset phase and its seasonal cycle" is unclear. What is the "monsoon onset" to be observed in GCM?

Reply: We thank the reviewer for his/her views on this seasonal progress. We would like to point out that CNTL simulated soil moisture over GP was higher than that observed throughout the year (Fig 5c). However, bias in CNTL simulated precipitation over GP was highest in June (Fig 2), that decreases in the subsequent months. In this study we have separated out June and July-September to show this seasonal progress of monsoon over India, especially over GP.

By "onset phase of monsoon over India" we mean early part of June month, when monsoon sets in over the southern tip of India and start progressing north-westward to cover the country in another about a month.

By "seasonal cycle" we mean seasonal cycle of Indian monsoon, that is related to seasonal northward migration of the intertropical covergence zone (ITCZ) up to the foothills of India.

Monsoon onset over GP has been defined in P6L19 - "We calculate onset date of monsoon over GP for CNTL and TRMM following the criterion used by Chakraborty et al. (2006), that is an onset is declared if the area averaged rainfall is more that 4 mm day^{-1} for at least five consecutive days after first of June". We will rewrite this sentence for more clarity.

7. Fig.6a,b Why the similar precipitation anomaly patterns, such as negative in northeast and positive in the central Indian subcontinent to BOB, even the GPDRY and GPWET setting are opposite soil moisture condition?

Reply: We have explained the cause of negative precipitation anomaly over GP (extending towards northeast) through moisture budget analysis in Fig. 7a (and explained in P9L3-7). In June (Fig. 7a), for GPDRY,net moisture advection slightly increased and evaporation reduced substantially, overall reducing precipitation compared to CNTL. For GPWET, net moisture advection reduced substantially and evaporation increased slightly , again reducing the precipitation compared to CNTL. Regarding positive anomalies over BOB, these are related to changes in wind circulation mainly (850 hPa wind differences are shown in Fig.6). Fig.6a,b show intensification of winds south of GP, extending over BOB. Southward shift in rainbands can cause this increase in precipitation over BOB, as compared to CNTL.

8. P8L33 Unclear explanation that "Higher moisture advection" from where to where?

Reply: Here we explain the low level circulation changes in GPDRY experiment as compared to CNTL. By "higher moisture advection" we mean in GPDRY, more moisture is advected into GP from surrounding areas, as compared to CNTL. We will modify statement for clarity.

References:

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