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Persistence of systematic errors in the Asian-Australian monsoon precipitation basic states in climate models: a way forward

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1. Persistence of systematic errors in simulating basic states

The annual cycle of the Asian-Australian monsoon (AAM) system can be regarded as the seasonal displacement of the large-scale Intertropical Convergence Zone (ITCZ), which is anchored by the north-south migration of the Indo-Pacific warm pool. In the respective hemispheres, intense solar heating over land during spring and early summer provide the necessary thermodynamic conditions for the occurrence of deep convection off the equator. The rainfall and diabatic heating associated with the AAM is perhaps the most vigorous of all the regional monsoon components in the globe. Yet, skill in monsoon prediction (days to seasons) by dynamical models remains low, partly due to our lack of understanding of the entirety of the monsoon system and our inability to *model the interactive processes* that govern it.

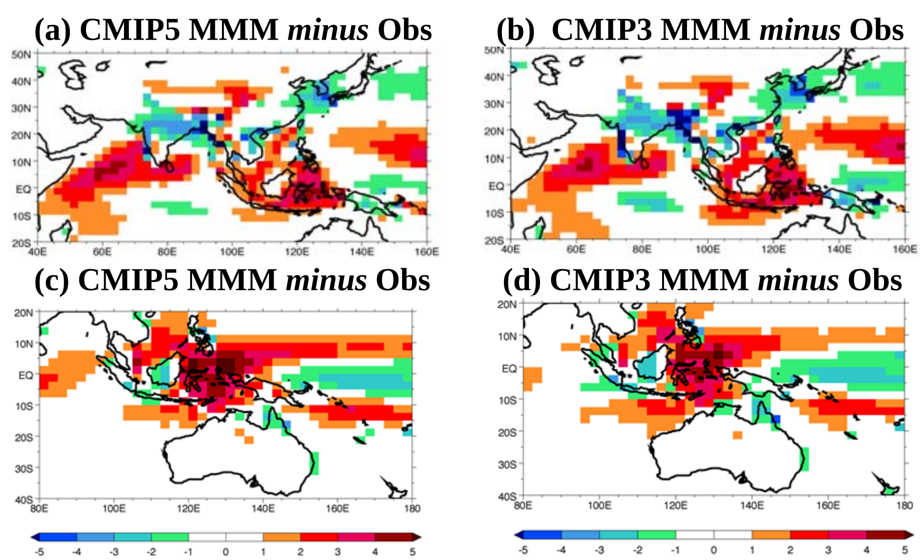

Fig. 1: Seasonal mean precipitation climatology difference (mm/day) between CMIP3/5 multi-model-mean (MMM) and GPCP observations: (a) and (b): boreal summer; (c) and (d): boreal winter.

Simulating the monsoon precipitation climatology remains a grand challenge. As seen in **Fig. 1,** the multi-model mean (MMM) errors for summertime precipitation relative to GPCP observations have shown little improvement in CMIP5 as compared to CMIP3 (Sperber et al. 2013). For the Asian Summer Monsoon, the MMM monsoon rainfall is weaker over South Asia, along the Meiyu-Baiu front, and the central-eastern equatorial Indian Ocean, and stronger over the western equatorial Indian Ocean and tropical West Pacific (**Figs. 1a-b**). For the Australian summer monsoon, it is excessive over most of the Maritime Continent, and deficient over northern Australia (**Figs. 1c-d**). Throughout the year, excessive rainfall is simulated over South China Sea – Maritime Continent regions, and CMIP5 models do not capture the annual cycle of the AAM (Sperber and Annamalai 2014). One implication is that uncertainties in future projections (e.g., IPCC 2013) of AAM mean rainfall may not have reduced from CMIP3 to CMIP5.

Solutions from an intermediate model show that diabatic heating (Q) associated with the AAM influences the global circulation (Sardeshmukh and Hoskins 1988). **Fig. 2** shows the vertical profile of Q, area-averaged over South Asian monsoon region (5^o−25^{o}N, 60^o−100^{o}E) during boreal summer from CMIP5 models (Cherchi et al. 2014). Compared to the reanalysis (solid black line), many models tend to have maxima at the mid-troposphere but their simulated amplitude is overestimated in the lower troposphere (900−700 hPa) and underestimated from 600−300 hPa, a feature readily apparent in the MMM composite (dashed black line). The lower troposphere peak may be attributed to misrepresentations in shallow convection. Some outliers, such as CSIRO-Mk3-6-0 and ACCESS1-3, do not show any appreciable vertical structure, and the simulated monsoon over South Asia is virtually absent in these models (Sperber et al. 2013). TRMM observations indicate that over the monsoon region the contribution from stratiform rainfall is about 40% to the Q intensity (Schumacher et al. 2004). In contrast, most of the CMIP3 models produce too much convective rainfall (95% of the total) and too little stratiform precipitation (Dai 2006). Given the persistence of errors (**Fig. 1**), we speculate that errors in the partitioning of total rainfall into convective-stratiform still persist in CMIP5, and may be one of the reasons for underestimation (overestimation) of Q in the layer 600−300 (900−700) hPa.

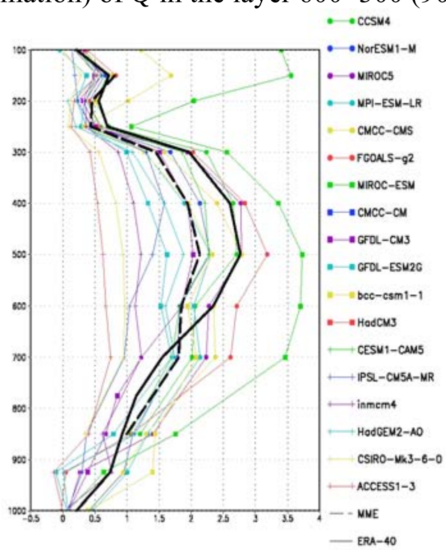

Fig. 2: Vertical distribution of Q (^{o}K/day) estimated from CMIP5 and ERA reanalysis (solid line). The multi-model-mean composite (dashed line) is also shown (adopted from Cherchi et al. 2014)

In summary, the rather slow progress in modeling in the last decade or so led us to wonder: *Has the scientific community reached a "plateau" in modeling mean monsoon precipitation?*

2. Way forward

It is now recognized that the AAM is a fully coupled ocean-land-atmosphere system that is also influenced by fixed orography. This recognition itself is, however, not enough. A systematic and well-coordinated approach in the identification of the coupled air-sea interactions, coupled land-atmosphere interactions, and flow-orography interactions that are critical in shaping the precipitation basic state needs to be carried out, and high-quality observations are needed to validate models and further improve model physics. This daunting effort requires the confluence of expertise in atmosphere, ocean and land-surface processes, and it cannot be accomplished with one group – *a multinational scientific effort with a multinational research funding is the only way forward*. Our focus, however, is restricted to improving understanding of coupled air-sea interactions and precipitation characteristics that govern the monsoon precipitation state over the open oceans, where large-scale precipitation errors persist in climate models. On this front, we propose three coordinated efforts: (i) coupled model experiments, (ii) process-oriented diagnostics, and (iii) direct observations. The possible role of land-atmosphere interactions and orography are discussed in related articles in this issue.

(a) Coupled model experiments

One of the major impediments for achieving the goal of monsoon modeling is the lack of sustained, oceanic, atmospheric and land observations. Given this lack, an alternative approach is to utilize a coupled ocean-atmosphere-land model that does develop a realistic, basic state. **Fig. 3** shows precipitation and SST climatology during boreal summer from satellite-based observations (**Fig. 3a**) and a solution to a coupled model (**Fig. 3b**), namely the Coupled model for Earth Simulator (CFES; Komori et al. 2008). Though not perfect (*e.g.*, the reduced precipitation over the tropical west Pacific), the solution realistically captures the spatial distributions and amplitudes of SST and rainfall over South Asia and the tropical Indian Ocean. In particular, the observed local maxima in rainfall over the eastern equatorial Indian Ocean is realistic, *a feature that most CMIP3/5 models fail to represent*. Recently, we performed a series of idealized coupled model experiments with CFES to investigate the influence of coupled processes in the equatorial Indian Ocean during the intermonsoons on the monsoon precipitation climatology (Annamalai et al. 2014; manuscript submitted), finding that the systematic precipitation errors noted in CMIP5 (**Fig. 1a**) are reproduced when the oceanic Wyrtki Jet was artificially weakened. Just how this result translates into removing the systematic errors in the CMIP3/5 models is yet to be resolved. A suite of similar process-oriented, model experiments (with other coupled models that have realistic basic state) needs to be performed to isolate all the air-sea interaction processes that shape the basic states in precipitation and SST over the AAM.

(a) TRMM/TMI **(b) CFES**

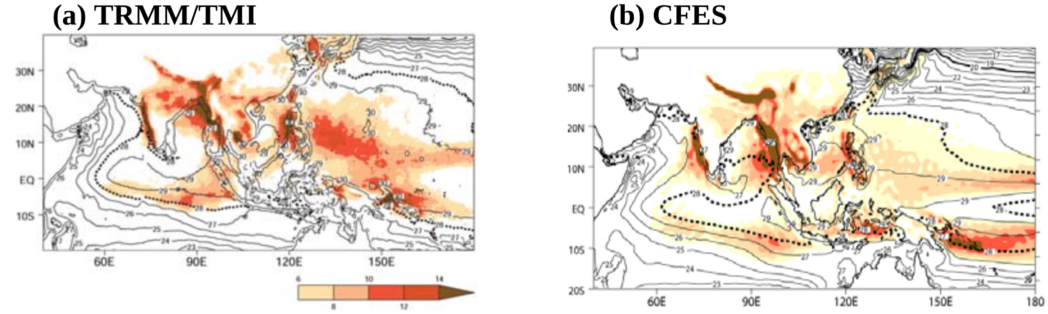

Fig. 3: Seasonal mean (JJAS) climatology of precipitation (mm/day; shaded) and SST (^{o}C, contour): (a) Satellite-based observations and (b) Coupled model for Earth Simulator (CFES). In precipitation only regions experiencing 6 mm/day and above are shown. The 28^{o}C isotherm is shown as heavy dotted line.

(b) Process-oriented diagnostics

We recommend process-oriented diagnostics that may provide pathways for model improvement. Some questions of particular interest include:

(1) While sufficiently high SST is a necessary condition for the monsoon rainfall, **Fig. 3a** suggests that the SST-precipitation association is not straightforward. For example, the SST threshold for occurrence of deep convection (rainfall > 6 mm/day) differs between the tropical Indian Ocean and tropical western Pacific and, despite SST exceeding 29^{o}C over the western equatorial Indian Ocean, there is little observed precipitation there – a feature CMIP3/5 models fail to represent. Thus, apart from SST, what are the "sufficient" conditions required to regulate moist convection, and are they adequately represented in models?

(2) Do climate models adequately represent the phase transition in convection (shallow to deep to stratiform clouds)? **Fig. 2** suggests that perhaps they do not. Bush et al. (2014) suggest that monsoon precipitation biases (and hence the vertical structure of *Q*) are sensitive to the entrainment and detrainment rates of convective parameterization. From observations and in models, what are the required thermodynamical conditions for convective phase transitions over the AAM region?

(3) The simulated SST in CMIP3/5 models is too cold over the tropical Indian Ocean (Levine et al. 2013) and tropical west Pacific (Annamalai et al. 2014; submitted). To what degree is the cool SST related to simulated systematic errors in precipitation and/or inadequate representation of oceanic processes? For instance, do models capture the salinity-induced barrier-layer over regions of high precipitation? Over the AAM, efforts on CMIP3/5 models' assessment have been primarily focused on atmospheric variables. A systematic evaluation of oceanic processes and their parameterization in ocean models need to be performed, and how they impact the coupled processes need to be ascertained.

(c) Observations

While process-based diagnostics of model solutions provide clues, do we have sufficient 3-d observations of key monsoon variables (moisture, temperature, vertical velocity, salinity, etc.) to validate the models? In our view, the answer is no. We won't be able to make advances in monsoon modeling, *until sufficient observational evidence exists to constrain model physics.*

1. Three-dimensional atmospheric states

Noting that the vertical structure of vertical velocity depends on model convective parameterizations employed in the reanalysis system, model biases are more severe in global reanalyses in the data-sparse region of the AAM (Mohan and Annamalai, manuscript in preparation). Moreover, direct radiosonde observations of thermodynamic variables are subject to significant biases (perhaps due to outdated instruments), which reanalysis systems do not incorporate. It has been suggested that *convergence of results from the different reanalysis products leans toward the "truth,"* but maybe that convergence occurs for wrong reasons! For example, along the eastern Pacific ITCZ, an examination of vertical structure of vertical velocity in various reanalyses suggests that its profile is bottom-heavy (e.g., Back and Bretherton 2006) whereas satellite observations suggest a top-heavy profile (Stachnik et al. 2013). One wonders where the "truth" lies? Direct observations can provide the much-needed answer.

Many studies have highlighted that the treatment of moist convection in global models as the single most important reason for their biases in tropical precipitation (e.g., Slingo et al. 1996). Results from observations, as well as cloud-resolving and numerical models, suggest that deep convection is sensitive to tropospheric humidity (e.g., Derbyshire et al. 2004; Tulich and Mapes 2010; Bretherton et al. 2004; Holloway and Neelin 2009). *Over the AAM, a first step is to plan for a series of ARM (Atmosphere Radiation Measurement) facilities (Stokes and Schwartz 1994;*

Mather et al. 1998) to observe the 3-d atmospheric states throughout the annual cycle along the AAM trough and over possible island-sites in the tropical Indian Ocean and west Pacific. A complementary approach is to replace the humidity sensors in the radiosondes so that reanalysis data can be constrained. Such sustained observations will provide robust evidence and insights into precipitation processes, and will serve as an invaluable resource for validating numerical model solutions and improving model parameterizations.

2. Three dimensional oceanic states

Recent efforts in the deployment of the Argo floats, Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) along the equatorial Indian Ocean are beginning to produce robust data sets that are valuable to understand the large-scale dynamics and assimilation of ocean models. *The vertical resolution of temperature, salinity and currents observed from these sources are, however, not sufficient enough to get the detailed vertical profiles that aid in improving ocean model parameterizations.*

The Indian Ministry of Earth Sciences (MoES) has launched a promising program, Monsoon Mission – an ambitious program that is focused on improving monsoon prediction. Under this mission and in collaboration with multiple research organizations and funding in the United States, the Air-Sea Interaction Regional Initiative in the Northern Indian Ocean (ASIRI)-Ocean Mixing and Monsoons (OMM) program is being carried out with an aim to understand the ocean sub-mesoscale processes and to improve their representation in models (Lucas et al. 2014). A related program, ASIRI-Effects of Bay of Bengal Freshwater Flux on the Indian Ocean Monsoon (EBOB) is focused on understanding the dynamics of freshwater, upper ocean processes, and air-sea interactions (Mahadevan 2014).

Similar to persistence of precipitation errors (Fig. 1), cold SST bias also persists over the northern Indian Ocean in CMIP3/5 models (e.g., Levine et al. 2013). Is it all due to systematic errors in representing the thin mixed layer and freshwater forced barrier-layer, perhaps due to the poor vertical resolution and misrepresentation of physics in their ocean components? To constrain the models on climatological time scales, do we have direct observations of seasonal variations in mixed-layer depth and barrier-layer thickness that are needed to estimate the mixed-layer heat budget over key regions of the tropical Indian Ocean? There are speculations that equatorial Wyrtki Jets aid in the maintenance of high-mean SST over eastern equatorial Indian Ocean, a region of intense precipitation throughout the annual cycle. Do we have enough observations to map the zonal extent of the Wyrtki Jet climatology, and to quantify its impact on SST? Truly, we need three-dimensional observations of temperature, salinity, and currents with high horizontal and vertical resolutions to quantify the contribution of various physical processes in maintaining the Indo-Pacific warm pool that anchors the AAM.

3. Conclusions

Motivated by the IPCC analysis and assessment reports (IPCC 2007; 2013), during the last decade or so numerous authors have evaluated the ability of climate models in representing the AAM and its variability. Despite dedicated efforts by the modeling community, there is a lack of substantial improvement in monsoon modeling and large systematic errors in the simulation of the basic state persist. Such a modest progress, in our view is due to the lack of high-quality observations (atmosphere and ocean) over the monsoon-influenced regions to constrain the model physics. *Our conclusion is that without such a focused observational effort, improving the physical processes in numerical models will be severely limited.*

In summary, we do not have adequate observations to know all of the processes that are involved in shaping the monsoon precipitation climatology and let alone modeling it! High-quality observations, in conjunction with coordinated coupled model experiments and process-based diagnostics are expected to foster our understanding and modeling of the monsoon precipitation climatology. It is true that huge investments are required for acquiring sustained high-quality observations. A coordinated effort among the international scientific community is required to approach different funding agencies to make progress in this very challenging and highly demanding endeavor. We hope to pursue that effort in the coming years.

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