CHAPTER 7

MODELLING MONSOONS

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The simulation of monsoons remains a challenging problem given the complexity of the multi-scale interactions and the modulating influences that operate on a broad range of time scales. Recent studies have demonstrated an improvement in the simulation of monsoons in CMIP5 relative to CMIP3, though many outstanding issues remain. For example, although mean state biases have been reduced in amplitude, the spatial error pattern remains virtually unchanged between the two vintages of experimentation. Systematic errors in the onset time of monsoons indicate that the simulated atmosphere-land-ocean interactions are not responding properly to the annual cycle of solar forcing. As such, the CMIP5 models have early monsoon onset over the Sahel and the North American domain, and late monsoon onset over India, the South American domain, and the Gulf of Guinea. This indicates that a regional process study approach is warranted for improving our understanding of atmosphere-land-ocean interactions inherent to monsoon development and onset. The simulation of intraseasonal variability remains a grand challenge problem, especially given its importance for initiating monsoon onset and being associated with precipitation extremes. Experimental prediction of intraseasonal variability suggests forecast skill to 3 weeks, with the potential for increased skill with the implementation of different projection basis function for boreal summer vs. boreal winter. Despite improvements in the simulation of the El Nino/Southern Oscillation, the interannual monsoon teleconnections are sensitive to biases in the regional rainfall that can compromise the response to the remote forcing. At best, interdecadal variations of Sahel rainfall are qualitatively captured in CMIP5, with the amplitude of the 1970's-1980's drought strongly underestimated. Conversely, mechanisms for observed interdecadal trends in rainfall over East Asia and northern Australia are yet to be understood, and these trends remain to be simulated. Higher horizontal resolution has been beneficial in the representation of orographic rainfall, as well as larger scale aspects of the circulation (e.g., Baiu front) though improvements to model physics are most essential for improving the simulation and prediction of monsoons.

1. Introduction

Understanding and forecasting monsoon variations remains a "Grand Challenge" problem. This undertaking, comprising diurnal through centennial time scales (including the effects of climate change), requires numerical weather prediction models, climate models, and regional models. From a physics standpoint, the fidelity in the representation of the land-ocean-atmosphere-cryosphere system is critical. This attests to the variety of forcings and time scales of interaction that influence monsoons (Webster et al. 1998).

Sensible heating and soil moisture are processes through which monsoons can be affected on short time scales. Snow cover was recognized a potential predictor of Asian monsoon (Blanford 1884, Becker et al. 2000) since it can affect the partitioning of sensible vs. latent heating, as does soil moisture. Remote large-scale teleconnections were also noted, especially the sea-level pressure variation over the Pacific (Walker 1924). Slowly varying boundary conditions, such as sea-surface temperature (Charney and Shukla 1981), impart memory to the system from subseasonal through centennial time scales, with the El Nino/Southern Oscillation (ENSO) being one of the major factors modulating monsoon variability across the globe. The multi-scale interactions of these factors, under a background of evolving greenhouse gas (GHG) forcing and aerosol impacts, conspire to make monsoon forecasting a difficult problem.

Traditionally, the term "monsoon" refers to the seasonal reversal of prevailing winds that is accompanied by excessive rainfall. Using the "global monsoon" definition of Wang and Ding (2006), Fig. 1 shows the observed and simulated CMIP5 multi-model ensemble mean representation of the global monsoon. With the exception of East Asia, and to a lesser extent the poleward extension of the North and South American monsoons, the mean model qualitatively represents the extent of the global monsoon domain. Typically, the multi-model mean shows better agreement with observations than any individual model, indicating that monsoon fidelity in individual models needs to be evaluated and improved.

While investigating the monsoon using a global approach is useful for summarizing model performance and isolating large-scale coherent climate change signals (Lee and Wang 2014), there are unique local aspects to each monsoon domain that require critical evaluation. The goal of this chapter is to highlight the model errors that are most critical for simulation and prediction of monsoons, and where possible highlight commonalities to errors across the domains that may benefit from coordinated process/diagnostic studies.

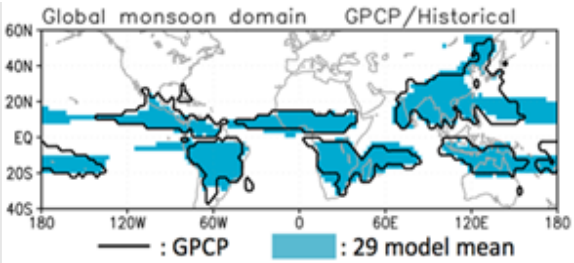

Fig. 1. Observed (thick contour) and simulated (shading) global monsoon domain, defined where the annual range of rainfall (difference between May-September and November-March) is greater than 2.5 mm/day. The observed domain is from GPCP data, and the multi-model mean precipitation is from CMIP5 historical simulations for 1986-2005. After Kitoh et al. (2013).

2. The Asian Monsoon

2.1. *Time-Mean State*

In terms of rainfall, the Asian summer monsoon extends from Pakistan to China, Korea, and Japan, including the western North Pacific (Fig. 1). Though the monsoon over these regions is mutually interactive (Annamalai and Sperber 2005), there are regional influences that distinguish the Indian component from the East Asian component. Though the meridional temperature gradient and the subsequent latent heat release after monsoon onset are the main drivers of the

monsoon, the monsoon over East Asia is also strongly affected by the subtropical high over the western Pacific and the East Asian Jet. The pressure gradient that develops in response to the temperature gradient drives the monsoon circulation. The low-level cross-equatorial flow and the southwesterlies that develop over the western Indian Ocean and the Arabian Sea contribute to the moisture transport that is the source of the monsoon rainfall, especially over India. Additional moisture from the Bay of Bengal and the South China Sea also contribute to rainfall over these regions and further downstream due to the influence of the west Pacific subtropical high.

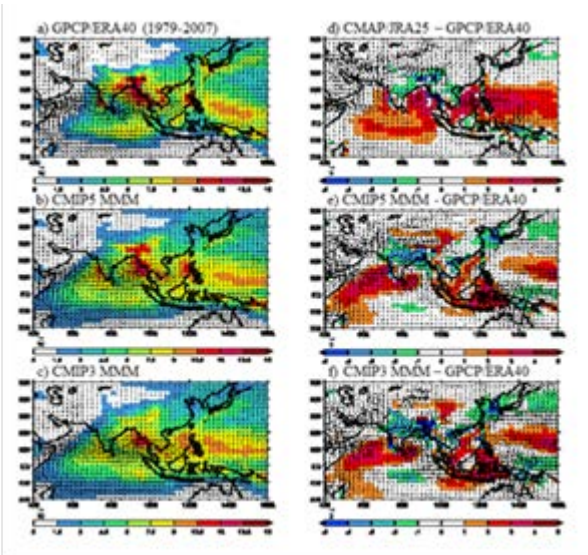

Fig. 2. June-September climatologies of precipitation (mm/day) and 850hPa wind vectors. (a) GPCP and ERA-40 (1979-2004), (b) CMIP5 MMM (1961-1999), and (c) CMIP3 MMM (1961-1999). Precipitation and wind error. (d) CMAP/JRA25 minus GPCP/ERA-40, (e) CMIP5 minus GPCP/ERA-40, and (f) CMIP3 MMM minus GPCP/ERA-40. After Sperber et al. (2013).

Intercomparisons of the Asian summer monsoon in CMIP3 (Meehl et al. 2007a) and CMIP5 (Taylor et al. 2012) simulations have been performed by numerous authors. Sperber et al. (2013) find that, in terms of the multi-model means, the CMIP5 models slightly improve upon the CMIP3 models for all of the diagnostics performed. Wang et al. (2013) also showed that the CMIP5 models are more skillful than the CMIP3 models in terms of additional Asian-Australian monsoon metrics. However, there are systematic errors that are consistent between the two vintages of experimentation (Figs. 2e and 2f). For example, the time mean rainfall error has a consistent pattern between CMIP5 and CMIP3, though the amplitude of the error is smaller in CMIP5 relative to CMIP3. Part of the error reduction results from the better simulation of precipitation maxima in the vicinity of steep orography, implying an advantage of using higher horizontal resolution in the CMIP5 models. The models systematically under-estimate the rainfall over India, China, Korea, and Japan, consistent with the underestimation of the monsoon domain in Fig. 1.

2.2. *Variability*

Over the Asian monsoon domain, the 30-60 day boreal summer intraseasonal variability (BSISV) causes active and break phases of monsoon rainfall (e.g., Yasunari 1979, 1981, Annamalai and Sperber 2005). Simulation of the BSISV has been problematic in climate and NWP models, in which eastward propagation of near-equatorial convection into the western Pacific and the northward propagation of convection near India are not well represented (e.g., Sperber et al. 2001, Waliser et al. 2003, Sperber and Annamalai 2008). Though most climate models still lack an adequate simulation of the BSISV, relative to CMIP3 there are an increasing number of

CMIP5 models that have an improved capability to simulate the BSISV (Sperber et al. 2013, Sabeerali et al. 2013). From examination of the CMIP5 multi-model mean, improvement is still needed to realistically represent the full extent of the northward propagation of convection over India, which may be related to the underestimate of mean state rainfall over northern India (Sperber et al. 2013). As a consequence the northwest to southeast rainband is not as tilted as observed. Also, improvement is need in representing the equatorial eastward propagation through the Maritime Continent into the western Pacific, and the subsequent north-northwestward propagation over the western tropical Pacific. Additionally, predictability of the BSISV is limited since the leading boreal summer intraseasonal mode is not related to slowly varying boundary conditions (Sperber et al. 2000).

On interannual time scales, the ability to predict regionally averaged ENSO SST anomalies (e.g., Niño3.4) with a 6-12 month lead-time led to the anticipation of skillful monsoon forecasts. However, the pattern of ENSO SST anomalies, which is less well forecasted, is critical to the characteristics of the teleconnection, as are the conditions over the Indian Ocean (Slingo and Annamalai 2000). Thus, even during years of strong ENSO forcing, seasonal monsoon forecasting is a challenge. Additionally, the strength of the ENSO-monsoon teleconnection exhibits pronounced decadal scale variability (Annamalai et al. 2007, Turner et al. 2007).

Over East Asia, a northward migrating zonal-oriented frontal zone of precipitation is a distinct feature in early summer. The CMIP3 models have difficulty in reproducing the latitude of the observed rainfall zones (Ninomiya 2009, 2011). Moreover the majority of the models do not reproduce realistic year-to-year variations in the Meiyu/Changma/Baiu frontal zones (Ninomiya, 2012). Large spread also exists in CMIP5 models over East Asia (Huang et al., 2013). The ability of models to reproduce these year-to-year variations is closely related to their ability to reproduce the modulating influences, including the East Asian summer monsoon, the North Pacific subtropical anticyclone, and the SST over the Pacific Ocean.

2.3. *Climate Change*

Difficulty in simulating the regional characteristics of rainfall and it variability in present-day climate model simulations poses a challenge for estimating the impact of climate change on monsoon variability (e.g., Turner and Annamalai 2012). At least two competing sets of processes associated with GHG changes impact climate change over South Asia, (1) thermodynamic changes whereby increased tropical SST gives rise to enhanced evaporation, increased moisture transport, and increased rainfall, and (2) dynamic effects whereby the monsoon circulation weakens due to a reduction in the meridional temperature gradient (e.g., Ueda et al. 2006).

A broad assessment of the prospective future change of the global monsoon has been performed by Lee and Wang (2014). This analysis evaluated 20 CMIP5 models, with the best 4 models used to generate a multi-model ensemble to assess climate change under RCP4.5. Their results suggest that (i) the global extent of the monsoon is not expected to change appreciably, although the monsoon over western Asia expands by ~11%; (ii) the

annual mean, the annual cycle range, and the percentage of rainfall that falls during the boreal summer are expected to increase; (iii) the monsoon onset will be advanced, and the monsoon withdrawal delayed, and compared to the Southern Hemisphere (SH), the Northern Hemisphere (NH) monsoon will increase significantly due to a change in the interhemispheric temperature gradient that enhances the Hadley circulation.

Under RCP4.5, Wang et al. (2013) indicate that the extent of the Asian-Australian monsoon domain will not change appreciably, though it is suggested that the domain may extend westward. Over Australia and the subtropical Asian region, the summer rainfall will make up a larger percentage of the annual mean. By the end of the 21st Century, an Asian-Australian Monsoon (AAM) rainfall increase of 4.5% is evident, primarily due to ISM and EASM increases. Due to hemispheric asymmetry in the temperature change, the rainfall increases over the ASM are larger than over the Australian monsoon domain. The ENSO-AAM teleconnection is expected to strengthen.

Increases in global monsoon area and global monsoon intensity are further amplified for RCP8.5 (Hsu et al. 2012, 2013; Kitoh et al. (2013). As discussed in Kitoh et al. (2013), over East Asia, (China, Korea, and Japan) average rainfall is projected to increase by ~7%, while over the remainder of the Asian summer monsoon domain the projected increase is ~13%. Extremes in precipitation during the Asian monsoon are also projected to amplify, with the seasonal maximum 5-day total rainfall increasing by ~20%, and the number of consecutive dry days increasing by ~5%. Different circulation changes are reported between CMIP3 and CMIP5 models in the Asian summer monsoon, i.e. westerly acceleration over the northern Indian Ocean in CMIP5 contrasted with slow-down of monsoon circulation in CMIP3 (Ogata et al., 2014).

Liu et al. (2012) performed a regional modelling study using RegCM3 with multiple large-scale driving datasets to downscale present-day and future scenarios A1B and A1FI over China. For present-day simulations the RegCM3 model is typically in better agreement with observations than the Community Climate System Model (CCSM) in terms of pattern correlation of surface temperature and precipitation, likely reflecting the increased resolution. Under climate change, the RegCM3 produces larger regional precipitation trends than CCSM, with both models showing greater warming under scenario A1FI than A1B. However such results must be treated with caution owing to the lack of ocean-atmosphere coupling in the regional modelling framework. The largest temperature increases occur over the Tibetan Plateau and northern China. However, there is substantial uncertainty in the projections as reflected by RegCM3 simulations forced by CCSM projections as compared to MIROC projections. Furthermore, it was found that present-day model biases affect future climate projections, indicating the need to reduce systematic model error (see also Levine et al., 2013 for the case of the Indian monsoon).

3. The Australian Monsoon

3.1. *Time-Mean State*

Tropical Australia is strongly influenced by the surrounding oceans, and is subject to a strong seasonal cycle of precipitation and

surface pressure, dominated by the Australian component of the Asian-Australian monsoon (e.g., McBride 1998). During the November to April period typically more than 90% of annual rainfall occurs across northern Australia (Nicholls et al. 1982) which also is traditionally referred to as Australia's wet season. The onset of the monsoon typically occurs in late December (Drosdowsky, 1996) but can vary considerably between regions.

On the large scale, the Australian monsoon is mainly driven by the differential heating of the continental land mass compared to the surrounding ocean in the build-up period of October-November resulting in the reversal of the meridional temperature gradient. This gradient produces a meridional circulation that brings moist air through low level westerlies across the maritime continent to tropical Australia (Hung et al. 2004). One of the defining characteristics of the large scale circulation is the reversal of the lower tropospheric winds from dry (wintertime) easterlies to moist (summertime) westerlies and a corresponding change to upper tropospheric easterlies (e.g. Troup 1961, Ramage 1971, Hung et al. 2004).

Coupled atmosphere-ocean climate models have traditionally shown difficulties in simulating the rainfall across tropical Australia during the monsoon season (Fig. 3). This has been shown for CMIP2 models (Moise et al. 2005), and CMIP3 models (Christensen et al. 2007, Colman et al. 2011, Moise et al. 2012) with many GCMs simulating considerable biases (often too wet across the northwest and too dry bias across northeast Australia). Compensating biases amongst the ensemble lead to a surprisingly good representation of the multi-model mean (Colman et al. 2011; also see Figs. 3f and 3g).

Pattern correlation skill scores of climatological precipitation and 850hPa wind (not shown) for the Australian monsoon show encouraging improvement in model skill from CMIP3 to CMIP5 (Moise at al. 2012, 2014), though the gross structure of the precipitation error is similar between the two vintages of models (Figs. 3m and 3n). Furthermore, there is an overall improvement in the seasonality of the Australian monsoon from CMIP3 to CMIP5, with most CMIP5 models better simulating the monsoon timing and very low rainfall rates outside of the monsoon season (Li et al. 2012). Some of the reasons for the lack of skill in the simulation of the monsoon have been attributed to SST pattern errors and also an unrealistic representation of the Indian Ocean dipole (Achuthavarier et al. 2012, Boschat et al. 2012). Meehl et al. (2012) reports on improvements in the pattern of rainfall in the Australian monsoon in CCSM4 compared to CCSM3 because of an improved representation of the surrounding SST's.

However, some significant geographical biases in the CMIP5 models are present (Moise et al. 2014, to be submitted), with precipitation extending too far south into the continental interior. An inverse relationship is also found between precipitation amounts and co-located continental surface temperature. Precipitation biases in models are related to differences in occurrence of convection and suppressed vertical motion.

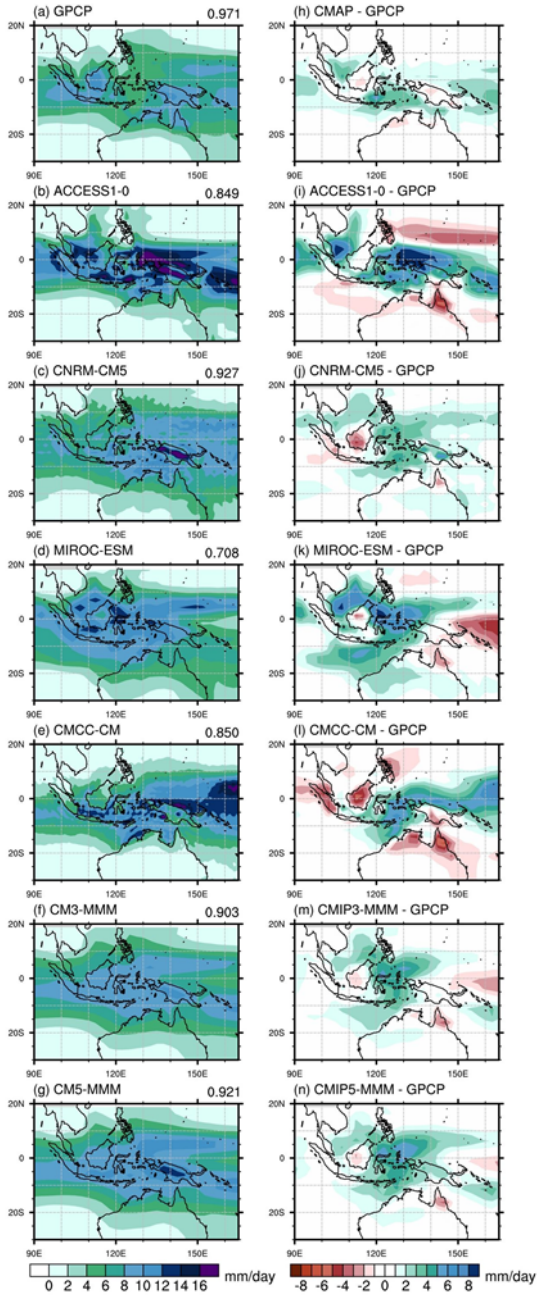

Fig. 3. a–g DJFM precipitation rate climatology from (a) GPCP, (b) ACCESS, (c) CNRM-CM5, (d) MIROC-ESM, (e) CMCC-CM, (f) CMIP3 MMM, and (g) CMIP5 MMM. Also given in (a) is the pattern correlation of GPCP with CMAP, and in b–g are the model pattern correlations with GPCP over the region 90°E–200°E, 30°S–20°N. (h) CMAP minus GPCP, i–n as b–g but for model minus GPCP. The units are (mm day^{-1}). GPCP and CMAP data is from 1979 to 1999 and the model data is from 1980 to 1999.

3.2. *Variability*

The annual cycle of precipitation over tropical Australia shows strong variability on higher frequencies related to synoptic-scale variability (e.g., Pope et al. 2009), with the Madden-Julian Oscillation (MJO) affecting the onset/bursts/breaks/retreat of the monsoon. Meehl et al. (2012) report intraseasonal variability of the Asian–Australian monsoon is also much improved, though it is still somewhat weaker in CCSM4 compared to observations. In CMIP5 errors in the phase speed and eastward propagation of MJO rainfall anomalies from the Indian Ocean into the western Pacific still persist (Hung et al. 2013).

Total precipitation in northern and eastern Australia shows marked interannual variability, being strongly influenced by ENSO. Interannual variability in precipitation is too weak in the model ensemble (although the model range in variability is considerable). Improvement can be partially attributed to the enhanced ENSO skill in CMIP5 compared to CMIP3. Most models reproduce the observed Australian monsoon-ENSO teleconnection (e.g., Cai et al. 2009, 2011), with its strength dependent on the ENSO variance. However, over the maritime continent, the simulated monsoon-ENSO connection is generally weaker than observed (Jourdain et al. 2013). Similar results have been reported by Catto et al. (2012a, 2012b) with respect to the evolution of North Australian SST's during composite El Niño and La Niña events.

Despite significant wind anomalies in the Indian Ocean related to Indian Ocean Dipole (IOD) events, the Australian monsoon-IOD relationship remains relatively weak both in observations and in CMIP3 and CMIP5 models (e.g., Jourdain et al. 2013).

3.3. *Climate Change*

The projected weakening of the large-scale tropical atmospheric overturning circulation has been detected in both CMIP3 (e.g., Vecchi and Soden, 2007; IPCC 2007) and CMIP5 models (Chadwick et al. 2013; IPCC 2013), and may have a direct impact on changes to the Australian monsoon. Similarly, the Walker circulation is projected to weaken under global warming (Power and Kociuba, 2011). Translating large scale changes of the tropical climate onto regional scales can incur large uncertainties, particular for rainfall (IPCC, 2007, 2013), and the Australian Monsoon region is especially affected. The factors contributing to this large uncertainty at different temporal and spatial scales are due to the complexity of the Australian monsoon system; the multitude of climate drivers impacting on the monsoon system; the model skill in representing these climate drivers, and finally the uncertainty surrounding possible changes to these drivers under enhanced greenhouse warming. Particularly over land, this can lead to inter-model differences in projected local rainfall changes becoming larger than differences between scenarios (Frieler et al. 2012; Moise et al. 2012), emphasizing the importance of process-based model evaluation. As a consequence, confidence in the projections is classified as medium to low, as acknowledged in the IPCC 5th Assessment report (Christensen et al. 2013).

In their recent study on global monsoon changes in CMIP5, Lee and Wang (2014) found that the four selected “best” models showed a summer monsoon rainfall increase in the Australian region, albeit with summer rainfall increases being much less than over the Asian domain. Additionally, the spatial extent of the Australian monsoon domain did not change significantly over land with some expansion eastward over the oceanic region. Similar results are found in Kitoh et al. (2013) from the analysis of 29 CMIP5 model results and Hsu et al. (2012) using high resolution uncoupled AGCM experiments. For RCP8.5 Kitoh et al. (2013) found that for the Australian monsoon average rainfall is projected to increase by ~7%. They also found earlier onset dates, later retreat dates, and longer monsoon durations.

In another study, Zhang et al. (2013 and 2014) used daily 850hPa winds and precipitable water data to analyse the change in the monsoon onset following the definition of Zhang et al. (2010). Analyzing both CMIP3 and CMIP5 models, the results indicated a delayed onset, with model-ensemble results showing a delay of 10-20 days in the tropics and around 7 days over the Australian continent. The majority of the models produced reduced monsoon duration, particular in tropical Sumatra-Java and nearby waters.

The significant uncertainties that accompany these model results is related to the models’ limited ability to reproduce the present monsoon climate and the large scatter among the model projections that limit the confidence in the projected changes. While these studies highlight the large uncertainty in

future changes to the mean state of the Australian monsoon, there is much less uncertainty in projected changes to both rainfall variability (at different time scales) and extreme rainfall events (IPCC 2013; Kitoh et al. 2013; Moise et al. 2014). For example, Kitoh et al. (2013) found that extremes in Australian precipitation are projected to amplify, with the seasonal maximum 5-day total rainfall increasing by ~15%, and the number of consecutive dry days increasing by ~7%. At the same time, projections for the formation of tropical cyclones (TCs) in the vicinity of tropical Australia suggest a decrease in TC genesis frequency (Tory et al. 2013) along with an intensification of TCs (Christensen et al. 2014).

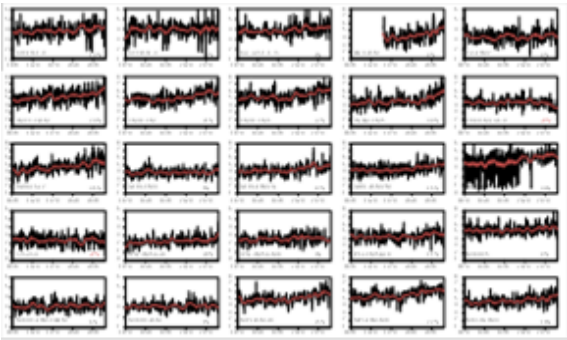

Fig. 4. Time series of sub-seasonal standard deviation of tropical Australia summer (December–March) monsoon rainfall for the 25 CMIP5 climate models for RCP-8.5 scenario. The variability (σ) is computed as the root-mean-square of the daily deviation from the seasonal mean of each individual year. Please note that the y-axis range differs for some models. The trend in seasonal standard deviation is shown (red line) and the percentages show the relative change in standard deviation in the future with respect to the past, i.e., (σ 2071—2100 – σ 1871—1900) / σ 1871—1900.

Australian monsoon rainfall variability is set to increase on inter-annual time scales (following its strong relationship to ENSO) and in particular on intra-seasonal time scales (Moise et al. 2014). Following the analysis from Menon et al. (2013), Moise et al. (2014) investigated the change in daily summer rainfall variability for the Australian monsoon region (land only) from 25 CMIP5 models (Fig. 4). On average they found a 15% increase with all but two models agreeing on the direction of change.

4. The African Monsoon

The African monsoon system is composed of the Western African Monsoon (WAM) and the Eastern African Monsoon. Prominent droughts and flooding events associated with the monsoon variability have often struck across different parts of sub-Saharan Africa and led to substantial economic and human losses (Peterson et al. 2012, Druyan 2011). African monsoon systems usually interact with monsoon systems from remote regions worldwide (Biasutti et al. 2003), suggesting that both regional and global perspectives are needed to improve our understanding of monsoon variability.

4.1. *Time-Mean State*

Improved understanding of the WAM has been gained through the African Multidisciplinary Monsoon Analysis project (AMMA, Redelsperger et al. 2006). The WAM system is a thermally direct land-ocean-atmosphere coupled circulation driven by the meridional gradients of dry and moist static energy in the boundary layer between the Gulf of Guinea and the continent from April through November (Lafore et al. 2011). The system is complicated, with the Saharan heat

low pressure minimum driving the convergence of two opposing low-level flows along the inter-tropical discontinuity. The resulting baroclinicity is responsible for the African easterly jet (AEJ), with the convection located within the inter-tropical convergence zone (ITCZ). African easterly waves are the primary weather systems, but understanding their interactions with mesoscale convective systems remains a scientific challenge. Lafore et al. (2011) exposed the critical role of the diurnal cycle of the atmospheric boundary layer (ABL), as well as the exchanges between different atmospheric layers and the large mesoscale fluctuations which feed back to the atmospheric circulations.

The WAM Modelling and Evaluation project (WAMME, Xue et al. 2010) and the AMMA-Model Intercomparison project (AMMA-MIP, Hourdin et al. 2010) have provided insights on the ability of GCMs to simulate WAM climate. They showed that AGCMs could reasonably simulate the spatial patterns and intensity of mean seasonal rainfall in West Africa. The main error is the failure to capture the regional circulations, including the AEJ and the upper-troposphere Tropical Easterly Jet.

For a range of time scales, RCM simulations from the COordinated Regional climate downscaling EXperiment (CORDEX; Giorgi et al. 2009, Jones et al. 2011) outperform the driving GCMs (Nikulin et al. 2012). Kim et al. (2013) further examined the monthly mean precipitation and surface air temperature produced by these 10 CORDEX RCMs and exposed the contrasting ability of models between the western and eastern parts of Africa, although significant biases are found in individual models depending on the region and seasons. Moufouma-Okia and Rowell (2009) showed that the HadRM3P regional model was more sensitive to lateral boundary conditions as compared to the initialization of soil moisture, while other studies of RCMs forced with the same reanalysis as lateral boundary conditions produce a wide-range of results. Thus, caution is warranted in drawing conclusions based on simulation with a single RCM.

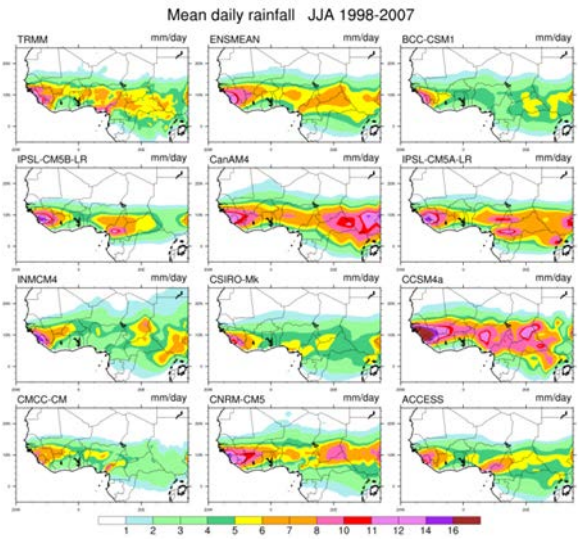

Fig. 5. June-August rainfall climatologies for 1998-2007 from (a) TRMM, (b) the CMIP5 ensemble mean, (c) BCC-CSM1, (d) IPSL-CM5B-LR, € CanAM4, (e) IPSL-CM5A-LR, (f) INMCM4, (g), CSIRO-Mk3.6.0, (h) CCSM4a, (i) CMCC-CM, (j) CNRM-CM5, and (k) ACCESS.

Coupled GCMs, such as those in CMIP5, have difficulties with capturing both the climatology and prominent modes of variability over Africa (Fig. 5). Models tend to misplace the latitudinal location of the tropical rainbelt, which is a major factor of rainfall variability in the tropics, and produce excessive summer rainfall over the Gulf of Guinea, leading to a substantial dry bias over

the Sahel region (Bielli et al. 2011, Cook and Vizy 2006). This error structure, prevalent in the CMIP3 and CMIP5 multi-model means, is similar to the difference between CMAP and GPCP rainfall (Sperber 2014, personal communication). However, in the models the excessive rainfall over the tropical Atlantic Ocean extends to 15ºS, and is inconsistent with the observational uncertainty.

4.2. *Variability*

The WAM intraseasonal variability and timing of the rainfall onset are critical issues for communities in West Africa, since most of the annual rainfall occurs in only a few months and even small variations can have a dramatic consequence. The meridional migration of the ITCZ with the Sun is not smooth but rather marked by a succession of active phases and pauses (Sultan and Janicot 2003). The first rainy season along the Guinean coasts occurs between April and June. It is followed by an abrupt northward shift of the tropical rainbelt from 5ºN to 11ºN, associated with the ITCZ, bringing rainfall to the Sahel. This abrupt northward shift of the WAM rainfall contrasts with the smooth retreat of the ITCZ, which gives rise to a second rainy season over the Guinean coasts in October-November. The mean onset date occurs between 24 and 30 June with a standard deviation of 8 days, depending on the variable used for the estimate.

Janicot et al. (2011) exposed three main modes of intraseasonal variability. Two modes, corresponding to the "quasi-biweekly zonal dipole" and the "Sahel" mode, have a mean periodicity of 15 days. The third mode is the "African MJO" mode, with a mean periodicity of ~40 days. All these modes depict a regional scale structure and can strongly influence rainfall and convective activity over West Africa.

Other important features of the WAM are the interannual and decadal variability. The ENSO phenomenon, Pacific Ocean, Indian Ocean, Mediterranean Sea, and the Atlantic Ocean have been identified as important drivers of the WAM rainfall at interannual time scales. The current consensus is that the Sahelian drought that developed during the second half of the 20th century is a result of remote effects of oceanic anomalies (Giannini et al. 2008). At decadal time scales and beyond, the variability of Sahelian rainfall coincides more closely with marked low frequency changes in the background state such as the Pacific decadal oscillation (PDO), the Atlantic multi-decadal oscillation (AMO) and the low frequency component of the Atlantic-Niño. In CMIP5, historical simulations reasonably capture the magnitude of the centennial Sahel drying over the span of the 20th century and confirm that anthropogenic forcings may have contributed to it (Biasutti 2013). Yet, the models do not reproduce the amplitude of observed oscillations at multidecadal time scales, suggesting that either oscillations in the forcing or the strength of natural variability are underestimated.

Unfortunately, little attention has been devoted to understanding the underlying physical mechanisms of East African monsoon (EAM) system. The EAM system possesses a number of unique features. The most important of these is the relative dryness, attributable to low-level divergent flow over East Africa in boreal summer. Most rainfall in the region occurs during the boreal spring and autumn season, when the flow pattern is more

or less convergent with the monsoon rainfall total being relatively low. The interannual variations of EAM rainfall, primarily associated with surface and atmospheric perturbations over the Indian Ocean basin, are also paired with ENSO, which can alter the local Walker circulation. In coastal areas of East Africa for example, moist conditions are usually associated with cool sea surface temperatures (SSTs) and related to vertical motions in the eastern Indian Ocean (Tierney et al. 2013, Webster et al. 1999).

Simulated features of the East African monsoon have been studied by Cook et al. (2012), using CCSM4. Comparisons have also been made to the atmospheric component of CCSM4 (CAM4) forced with observed SSTs, in order to isolate the contribution of land-atmosphere processes in the model errors. The results indicate that CCSM4 produces an improved simulation of the EAM rainfall compared to the CAM4. While CCSM4 and CAM4 both reasonably capture the spatial distribution of seasonal rainfall totals, but with slightly higher values, the intraseasonal variability of the EAM rainfall is more realistic in the coupled model simulations.

4.3. *Climate Change*

Accurately predicting the diversity of climate regimes across Africa poses major challenges for coupled general circulation models (GCMs). This is due partly to our limited understanding of the complex interactions across weather and climate time scales, the interactions between local and remote processes, and the coarse horizontal grid resolutions used in coupled GCMs. The CMIP5 coupled GCMs strengthen the previous assessment for a substantial role of anthropogenic emissions in driving rainfall changes in the Sahel.

Regarding future projections, the IPCC 4th Assessment Report indicates that the CMIP3 coupled GCMs (Meehl et al. 2007b) disagree on both the magnitude and sign of anthropogenically forced rainfall changes over Africa (Druyan 2011, Caminade and Terray 2010). Patricola and Cook (2010) used the Weather Research and Forecasting (WRF) RCM to downscale nine CMIP3 simulations and found that the precipitation change signal is very mixed over West Africa in the second half of the twenty-first century.

Compared to the CMIP3 results, in CMIP5 there has been little evolution of model performance in terms of both the present-day model errors and uncertainty in future projections (Roehrig et al. 2013). In CMIP5 80% of the simulations suggest ~20% drying of western Sahel and 75% of the models project increased rainfall over the eastern Sahel, with large spread in the amplitude of the projected change in rainfall. Thus, over the whole of the Sahel, the CMIP5 RCP8.5 average precipitation response is rather muted, with a projected increase of only 2.4%. The projected change in rainfall extremes are rather larger, with the seasonal maximum 5-day total rainfall increasing by ~14%, and the number of consecutive dry days increasing by ~9% (Kitoh et al 2013). However, given difficulties in simulating the phase of the diurnal cycle of precipitation and the propagating mesoscale systems that contribute the bulk of rainfall to the Sahel, and the errors in the simulation of SST in the tropical Atlantic, Roehrig et al. (2013) indicate “that over West Africa, CMIP5 models have not reached yet a degree of maturity that makes it possible to directly rely on them to anticipate

climate changes and their impacts, especially with regard to rainfall."

5. The South American Monsoon System (SAMS)

5.1. *Time-Mean State*

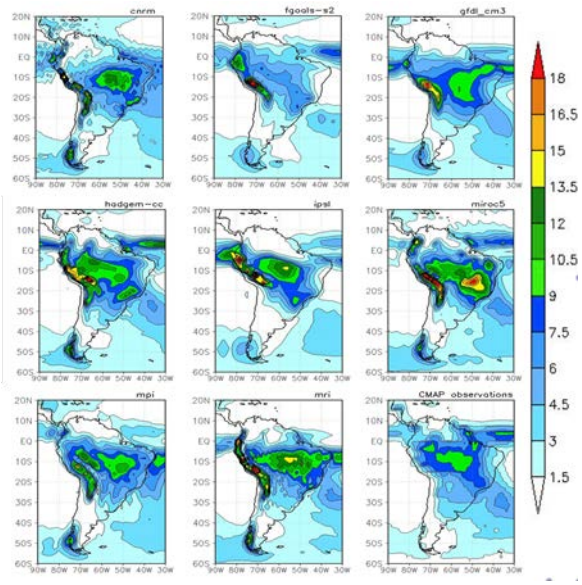

Fig. 6. Rainfall climatology (mm/day) for December-February 1979-2010 for (a) CNRM, (b) FGOALS-s2, (c) GFDL-CM3, (d) HadGEM2-cc, (e) IPSL-CM5A-LR, (f) MIROC5, (g) MPI-ESM-LR, (h) MRI-CGCM3, and (i) CMAP.

The CMIP5 models underestimate rainfall in Amazonia during both wet and dry seasons (Yin et al. 2012). Most models overestimate convective rainfall and underestimate large-scale precipitation during the wet season. This is a consequence of complex feedbacks between the land surface heat flux, rainfall, radiation, and the large-scale circulation. Jones and Carvalho (2013) reported that only a few CMIP5 models were able to simulate the maximum precipitation over the core of the monsoon region, as seen in Fig. 6, while others had serious deficiencies, such as "excessive precipitation over Northeast Brazil, displaced ITCZ, double ITCZ, and too little precipitation over eastern Amazon." All ten models analyzed in their paper show a trend of delayed SAMS retreat dates over the later portion of the historical runs, consistent with observations, with several models showing average retreat dates consistent with the observed climatology.

5.2. *Variability*

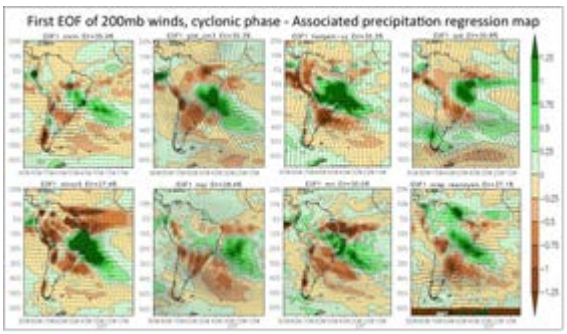

Fig. 7. Regression maps of January-March (JFM) 200hPa wind on PC1 from the EOF analysis of the 200hPa wind (arrows, m s^{-1}) over 50ºS-10ºS, 70ºW-0ºW domain for seven CMIP5 models and the NCEP-NCAR reanalysis dataset, for the cyclonic phase. Also shown are the regression maps of the JFM precipitation on PC1 (shading, mm day^{-1}), multiplied by the mean value of PC1 during years of strong cyclonic phase (when PC1>σ(PC1) or <-σ(PC1)).

The interannual variability of SAMS has been investigated using EOF analysis of the January-March (JFM) 200hPa mean winds over 50°S-10°S, 70°W-0°W (Robertson and Mechoso 2000). This mode consists of an equivalent barotropic vortex centered on the coast of southeast Brazil (around 30°S, 45°W). As seen in Fig. 7, for the CMIP5 models there are intermodel differences in the location and

intensity of the vortex, as well as in explained variance. The cyclonic (anticyclonic) phase of the vortex corresponds to an enhanced (weakened) South Atlantic Convergence Zone (SACZ), and to anomalously low (high) precipitation over most of La Plata basin (Ma et al. 2011). During the anticyclonic (cyclonic) phase the low-level winds bring air with lower (higher) moist static energy to the SACZ from the Atlantic (Amazon) resulting in decreased (enhanced) convection. During years with a strong cyclonic (anticyclonic) phase, this mode of variability accounts for a large part of the precipitation anomalies in both the simulation and the observation. The relationship between wind and precipitation anomalies is generally consistent with the theory of convective margins (Ma et al. 2011) and with the ventilation mechanism (Lintner and Neelin 2010).

5.3. *Climate Change*

Precipitation over South America during the wet season is projected to increase in the CMIP5 models (Seth et al. 2013; Kitoh et al. 2013). A similar increase was obtained by the CMIP3 models (Seth et al. 2010) and is present in the historical record (Skansi et al. 2013). The percentage change in median precipitation for the SAMS is a 1.5% increase within the RCP4.5 emissions scenario and a 2.4% increase within the RCP8.5 scenario by the end of the 21st century (Kitoh et al. 2013). The precipitation increase seems mostly related to an intensification of heavy rainfall, particularly over the Amazon and southeast South America, rather than to increases in the duration or frequency of consecutive wet days (Skansi et al. 2013). During the monsoon months there is a projected increase of ~18% for the model median five-day seasonal maximum in precipitation and the median number of consecutive dry days by 2100 in the RCP8.5 scenario (Kitoh et al. 2013). The seasonal amplitude of the monsoon, inferred from precipitation, moisture, temperature and monsoonal circulation, is also projected to increase by 30% from the current amplitude by mid-century (Jones and Carvalho 2013). Lastly, the length of the monsoon season is generally projected to increase. By mid-century, the ensemble mean of selected CMIP5 models projects an earlier onset by 14 days and a later demise by 17 days in the RCP8.5 scenario (Jones and Carvalho 2013). However, the different precipitation indices used to quantify this change in different studies result in somewhat inconsistent results (Kitoh et al. 2013).

6. The North American Monsoon System (NAMS)

6.1. *Time-Mean State*

Compared to the CMIP3 results, in CMIP5 the mean annual cycle of monthly precipitation over a core NAMS domain shows little improvement in magnitude, but clear improvement in phasing (Geil et al. 2013). For most models, NAMS onset is early and monsoon retreat is poorly captured. This difficulty has been associated with an unrealistic flux of low-level moisture from the tropics into the NAMS region that persists after the monsoon season. There is large intermodal variability in the simulation of NAMS.

The North American Monsoon System (NAMS) has been evaluated using the CAM4 with three different dynamical cores at

multiple horizontal resolutions. The three dynamical cores are Spectral Eulerian, HOMME, and MPAS. As seen in Fig. 8, at T85 the ITCZ is too weak and there is too much precipitation over the Sierra Madre Occidental (SMO). The T341 simulation is more successful in representing the ITCZ and precipitation in the USA states bordering the Gulf of Mexico. HOMME, at 110 km resolution, is more successful than T85 in the precipitation over the SMO, but there is still too little precipitation over the Gulf States, Panama, and Costa Rica. HOMME at 27 km resolution can better simulate the ITCZ, but precipitation is too high over the SMO. It is hypothesized that higher resolution simulations can improve the overall spatial characteristics of the ITCZ and reduce dry biases in the southeastern U.S. and northern Mexico by better resolving the mesoscale dynamics contributing to the NAMS.

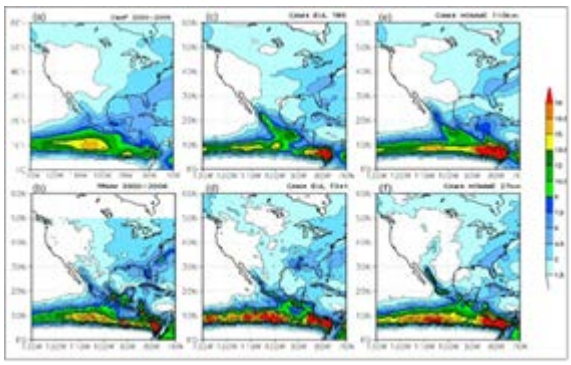

Fig. 8. Precipitation climatologies from: (a) CMAP data at 2.5° global resolution; (b) TRMM data at 0.25° global resolution; (c) CAM4 with the spectral Eulerian dynamical core at ~1° global resolution (T85); (d) CAM4 with the spectral Eulerian dynamical core at ~0.25° global resolution (T341); (e) CAM4 with the HOMME dynamical core at 110km global resolution (HOMME 110km); and (f) CAM4 with the HOMME dynamical core at 27km global resolution (HOMME 27km) in the NH summer (JJA). Climatologies are for 2000-2006.

Previous results, performed with the NCEP Global Forecasting System (GFS; Mo et al. 2005) and CAM3 (Collier and Zhang 2007) also indicate that increased model horizontal resolution has a positive impact on the simulation of NAMS. In GFS, precipitation over the southwest U.S. and northwest Mexico was improved when the resolution was increased from T62 to T126. Relative to CAM3 T42, T85 rainfall over the SMO region is better simulated, and a phase bias in the diurnal cycle is somewhat reduced. Also, T42 poorly simulates the month-to-month evolution of the wet season over northwestern Mexico and Arizona, while these biases are considerably reduced with T85.

6.2. *Climate Change*

For the NAMS, projected climate changes to the end of the 21st century show a weakening of the monsoon through a weakening and poleward extension of the Hadley cell (Lu et al. 2007; Vera et al. 2013). The CMIP5 models project an overall decrease in annual mean precipitation (Cook and Seager 2013) and a decrease in total monsoon rainfall by ~7% in the RCP8.5 scenario in the core NAMS region by 2100 (Kitoh et al. 2013). The CMIP5 models show that in RCP8.5 there are significant decreases in early monsoon (June-July) precipitation and increases in late monsoon (September-October) precipitation; this is consistent with CMIP3 model results (Cook and Seager 2013; Maloney et al. 2014). CMIP5 models consistently project an increase in summer mean temperatures, which may be associated with higher extreme

temperatures (Duffy and Tebaldi 2012) and may also impact extremes of precipitation. The median number of consecutive dry days is projected to increase by ~11% in RCP4.5 and by ~23% in RCP8.5 by 2100 (Kitoh et al. 2013). Additionally the median seasonal maximum in five-day precipitation is projected to increase by ~3% in the RCP4.5 scenario and by ~6% in the RCP8.5 scenario by 2100 (Kitoh et al. 2013).

7. Challenges

A variety of mean state errors can be found over the various monsoon domains. For the Asian monsoon, improvement is needed in the simulation of the mean state and the annual cycle phasing and amplitude (Sperber et al. 2012). While coupled ocean-atmosphere simulations are critical for establishing monsoon teleconnections (Wang et al. 2005), SST errors can also lead to biases in monsoon. For example, Levine et al. (2013) find that CMIP5 models that have a substantial cold bias over the Arabian Sea have a delayed onset due to a weakened moisture flux. Other possible contributions include inadequate simulation of land surface processes and sensitivity to convection scheme parameters (Chen et al. 2010, Zou et al. 2014).

Over Africa present-day simulations have difficulties with capturing the climatology and prominent modes of variability. Additionally, the simulation of reliable atmospheric water cycles associated with the African monsoon systems requires major improvements in the physical parameterizations of climate and weather models. Importantly, more attention needs to be devoted to understanding the physical mechanisms and variability of the East African monsoon system. Over Australia the CMIP5 mean precipitation extends too far southward into the continental interior. For SAMS, most models overestimate convective rainfall and underestimate large-scale precipitation during the wet season, and underestimate rainfall in Amazonia during both the wet and dry seasons. For NAM, extension of rainfall over northern Mexico and the southern U.S, is problematic, as is the representation of the coastal vs. ocean rainfall.

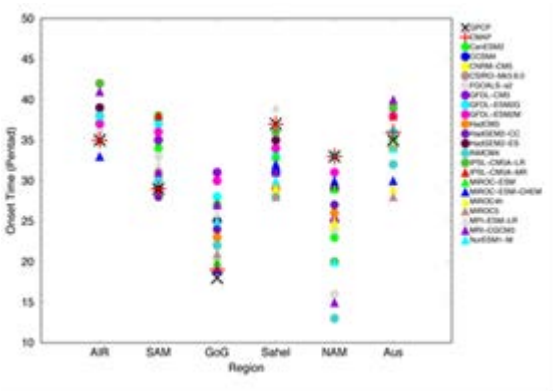

Fig. 9. The pentad of climatological summer monsoon rainfall onset from GPCP and CMAP (1979-2004) and from 21 CMIP5 historical simulations (1961-1999). See Sperber and Annamalai (2014) for a discussion of the technique of fractional accumulation for model evaluation, and for the spatial extent of the various domains. Note for Aus and SAM the pentads were reordered to July – June prior to analysis.

The biases in the annual cycle of monsoon precipitation are particularly acute, and regionally diverse. As seen in Fig. 9, Sperber and Annamalai (2014) analyzed climatologies of pentad rainfall from GPCP, CMAP, and 21 CMIP5 historical simulations. From an evaluation of the fractional accumulation of rainfall they found that the models were systematically late in monsoon onset for All-India rainfall, the South American monsoon, and the Gulf of Guinea. However, over the

Sahel and the NAM domain the models were systematically early in the onset of monsoon rainfall. For WAM, the models poorly represented the sudden transition of rainfall from the Gulf of Guinea to the Sahel. Similarly, the models did not represent well the ocean vs. land behavior for NAM.

Pronounced interdecadal variations in rainfall are observed over all monsoon land domains (Zhang and Zhou 2011). Adequate simulation and understanding of processes that drive secular trends in rainfall variability are basic challenges. Over the Sahel, simulation of the observed decadal drying trend is a particularly daunting task for most GCMs, due to the wide range of physical processes competing to drive the rainfall trend. Similarly, over Australia one of the major challenges for current climate models is the failure to simulate the recent upward trend in northwest Australian rainfall. Neither the CMIP3 nor CMIP5 models are able to capture this trend, with suggestions that it is related to either aerosols (Rotstayn et al. 2012) or changes in diurnal/synoptic patterns of rainfall (Catto et al. 2012c; Berry et al. 2012). Similarly, for the past 60 years, the East Asian summer monsoon has been weakening, resulting in a tendency toward increased droughts in northern China and floods in the Yangtze River Valley. The long time scales suggest that teleconnections remote from the monsoon domains need to be better understood. This is also true on interannual time scales, where for example, excessive snow cover over Eurasia has been linked to dry biases of the Indian summer monsoon (Saha et al. 2012). Also remaining are systematic biases that are particularly important at regional scales. These biases include adequate simulation of SST and its variability, and the representation of the multi-scale interactions that modulate monsoons.

The impact of aerosols on the Asian monsoon rainfall remains a subject of much debate, and adequate modelling of both their direct and indirect effects is still a source of uncertainty for attribution studies (Song et al., 2014), present-day climate reproducibility and future climate change scenarios. The elevated heat pump hypothesis is a potential, but debated, mechanism by which aerosols influence the Asian monsoon (Lau and Kim 2006, Lau et al. 2006). Over Africa the role of aerosols, including wind-blown dust, need further investigation to assess their impact on the radiation budget and hydrological cycle.

While improved representation of monsoon variability is intimately tied to realistic physical processes, higher horizontal resolution has a demonstrated benefit for the simulation of monsoons. Over Asia there is improvement in the simulation of the southwest monsoon circulation, orographic rainfall, and the monsoon trough over the Bay of Bengal. Along the monsoon trough, synoptic scale disturbances and mesoscale convective systems are noticeably improved (Sabin et al. 2013), as is the Baiu frontal structure, and orographic rainfall over East Asia (Kitoh and Kusunoki 2008). Over North America the ITCZ and precipitation in the states bordering the Gulf of Mexico improve at higher resolution, and over South America circulations are improved with better representation of the Andes Mountains. Additionally, increased vertical resolution in the upper ocean has been shown to be important for capturing diurnal variations of sea surface temperature. These diurnal variations project onto intraseasonal time scales, giving rise to the SST perturbations

that improve the organization of intraseasonal convection (Bernie et al. 2005, Klingaman et al. 2011).

Estimating the potential impact of climate change is a daunting problem, especially in light of model bias. Until recently, the typical approach was "one-model, one-vote" when performing a climate change study. Recently, a broader range of model evaluations has been facilitated due to open access to the CMIP database (Taylor et al. 2012). As such, a wider variety of process evaluations and skill metrics have been applied to the historical simulations. This has promoted the selective use of models in climate change assessments, by critically assessing the quality of the historical simulations, with the goal of reducing uncertainty in projections. For example, in the case of Asian monsoon, the spatial pattern of the mean state precipitation, the quality of ENSO, and the ENSO-monsoon tele-connection have been used as filters for model selection (e.g., Annamalai et al. 2007). Alternatively, for global monsoon assessments, the ability of models to represent the leading modes of the annual variation of precipitation has been used (e.g., Lee and Wang 2014). Thus, for relevant processes and interactions the sub-selected models exhibit better overall skill in their simulation of the present-day interactions as compared to the full suite of model. An important byproduct of the sub-selection process is that it provides modelers with an indication of the relevant processes that need to be improved in the next generation of models.

A hallmark test of any model is its ability to make predictions. From a practical standpoint, intraseasonal prediction is a highly coveted, given the impact of the ISO on monsoon onset, extreme rain events, flood and drought conditions, and the associated practicalities for farming and hydrometeorological services. The modal structures of the MJO (e.g., Wheeler and Hendon 2004) and the boreal summer intraseasonal variability (BSISV; e.g., Lee et al. 2013) are well known from observations. As such experimental real-time forecasts of the MJO and BSISV are ongoing through the effort of the WGNE MJO Task Force and the contributions of most of the world's numerical weather prediction centers (Gottschalck 2010). From projecting the relevant NWP forecast variables onto the observed basis functions there is useful skill out to about 3 weeks for predicting the large-scale intraseasonal structure. While the life-cycle of the MJO and the BSISV has been characterized in detail (Sperber 2003, Annamalai and Sperber 2005), a theory of intraseasonal variability still eludes us (Hendon et al. 2011). As such, progress in modelling the intraseasonal variability has been limited (Hung et al. 2013, Sperber and Annamalai 2008, Sperber et al. 2013), with sensitivities to the details of convective parameterization and their interaction with environmental moisture identified as potential limiting factors in our ability to model intraseasonal variability (Kim et al. 2014). Modeling intraseasonal variability has been recognized as a grand challenge problem, with a coordinated international effort underway to improve our understanding of the essential processes that give rise to this mode of variability (Petch et al. 2011).

The challenges of predicting and simulating monsoon variability from diurnal through centennial time scales attests to the broad scope of processes and multi-scale interactions that need to be represented with

fidelity in order to produce more realistic simulations of monsoons.

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