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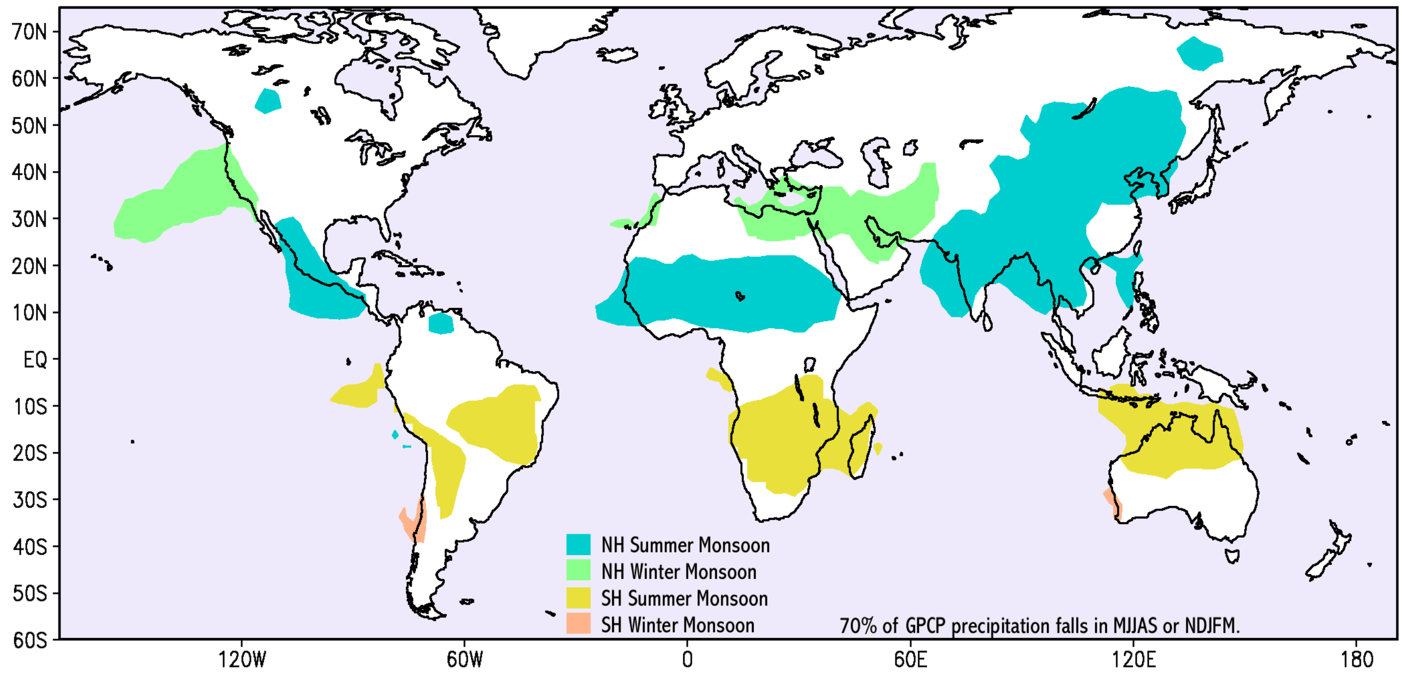
Special Issue on Monsoons: Advancing understanding of monsoon variability and improving prediction

Produced by the new jointly-sponsored CLIVAR and GEWEX Monsoons Panel



Regions where at least 70% of annual precipitation occurs in the 5-month seasons indicated. This is only one of many possible definitions of monsoon regimes around the globe. Data are from GPCP version 2.5 For 1979-2008 provided by P. Dirmeyer

CLIVAR Ocean & Climate: Variability, Predictability and Change is the
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Editorial

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2015 will be an important CLIVAR year with the new Climate Dynamics Panel and joint CLIVAR-GEWEX Monsoons Panel initiating their work, the implementation of three CLIVAR Research Foci, work underway for the production of the CLIVAR Achievement Report, the CLIVAR Science Plan and planning for a CLIVAR Open Science Conference envisioned for third quarter 2016. Following up from the very successful pan-CLIVAR meeting this summer in The Hague, the CLIVAR SSG met in Moscow in November, in particular to review progress with regards to the Research Foci. The meeting report is available here: http://www.clivar.org/about/ssg.

Three of the Research Foci have been endorsed for implementation in 2015 by the SSG, namely Decadal Climate Variability and Predictability, Consistency Between Planetary Energy Balance and Ocean Heat Storage and ENSO in a Changing Climate. The Research Foci on Monsoons and on Marine Biophysical Interactions and Dynamics of Upwelling Systems (in collaboration with IMBER) will further develop their plans, to be reviewed by the SSG by the end of this year with a view towards implementation in 2016. The CLIVAR Research Focus areas on Sea Level Rise and Extremes are being implemented as WCRP Grand Challenges.

This Exchanges Special Issue is an opportunity for CLIVAR to highlight key areas that will be addressed by the Monsoons Panel (ToRs: http://www.clivar.org/panels-and-working-groups/monsoons). We thank Drs. Paul Dirmeyer and Andrew Turner, Panel Cochairs, for their work as Guest Editors of this issue, introducing the Panel and assembling such a far-reaching suite of articles that give a flavor of the themes that will be fostered by the Panel. The Panel will hold its meeting this July in Prague and will work to define concrete activities that will be coordinated by the panel within the next 3-5 year time frame.

The Monsoons Panel is supported by Dr Rokkam Rao and staff of the International CLIVAR Monsoons Project Office (ICMPO), a node of the International CLIVAR Project Office (ICPO) hosted by the Indian Institute of Tropical Meteorology (IITM) located in Pune, India,This arrangement is part of the newly established distributed ICPO, designed to take advantage of the strengths of the participating institutions and fostering an ICPO that is truly international in nature.

Introduction to the CLIVAR Exchanges Special Issue on Monsoons

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It is with great pleasure that we introduce this Special Issue of Exchanges on monsoons. The Special Issue coincides with the reorganization of monsoon research efforts within the World Climate Research Programme. Until recently, CLIVAR had three separate panels on the topic, each focused on a specific geographical area: the Americas, Africa, and the Asian-Australian region. However, monsoons are a global phenomenon (see the cover figure) and overall progress in our scientific understanding of monsoons will benefit by the interaction of individuals and groups that study these various regions. Furthermore, the efforts of the Global Water and Energy Exchanges (GEWEX) project are highly relevant to the terrestrial and hydro-thermodynamic aspects of monsoons. As a result, a single Monsoons Panel spanning both CLIVAR and GEWEX has been formed with membership drawn from both communities. The new panel will report to both CLIVAR and GEWEX Scientific Steering Groups.

Working groups under the new panel will continue to lead the regionally-focused monsoon research in each of the three areas of globe. Meanwhile, the new panel is defining concrete activities to be fostered in the coming years, coordinating the regional working groups, and acting as a hub to facilitate meetings and linkages among international research efforts. Advancing understanding of monsoon variability and improving prediction remain the principal goals promoted by the new Monsoons Panel, but greater emphasis is being placed on linkages across scales and to phenomena that have historically been outside the purview of classical monsoon research. Observation and modeling are still the cornerstones of the research efforts, but we seek to bring new methods and fresh perspectives to the problem that can enhance monitoring, advance diagnostic efforts, and improve component and coupled models. Key to these efforts will be the development of new and better process studies, coordination with relevant modeling efforts including those related to climate change, and empowering the next generation of bright young scientists from around the world to advance our knowledge of monsoon systems.

Ultimately this knowledge must make its way back to national and local interests to improve predictions, and ultimately socioeconomic well-being. The articles in this Special Issue span the geographic range of the world's monsoons, but also introduce phenomenological perspectives including the role of land-atmosphere interactions, sub-seasonal variability and the consequences of human activity on monsoons. We hope that these articles will help you get up-to-speed on the current state of monsoon research and what leading researchers in the field see as the next important challenges. We thank all the authors for their contributions, and special thanks to Dr. Anna Pirani for her tireless work to herd us Monsoon Cats.

Introduction of the International CLIVAR Monsoon Project Office (ICMPO)

Rokkam R. Rao, Ramesh H. Kripalani, K.P.Sooraj and A. Suryachandra Rao

Indian Institute of Tropical Meteorology, Pune, India

Introduction

The International CLIVAR Project Office (ICPO) was initially hosted at the Max Plank Institute in Hamburg, Germany and in 1998 it moved to the National Oceanography Centre (NOC) in Southampton, UK, where it was supported by the UK Natural Environment Research Council (NERC), until April, 2014. Since then, the ICPO is supported by the State Oceanographic Administration/First Institute of Oceanography (FIO), the Indian Ministry of Earth Sciences/Indian Institute of Tropical Meteorology (IITM) and NASA, NOAA, NSF and DoE through US CLIVAR. A distributed ICPO structure has been formed that builds on the strengths of each of the institutions offering support for the international coordination of CLIVAR activities. See here for more information: http://www.clivar.org/about/icpo

The ICPO consists of two offices, hosted by China and India, and contract staff, supported by the USA. The offices, or two nodes:

- International CLIVAR Global Project Office, SAO-FIO, Qingdao, China
- International CLIVAR Monsoon Project Office, IITM, Pune, India

Overall management and coordination of the ICPO is the responsibility of the ICPO Executive Director who also acts as the primary interface with the CLIVAR SSG co-chairs and the Director, WCRP. The Executive Director is assisted by a Deputy Executive Director.

Hosting of an ICPO node by the Indian Institute of Tropical Meteorology (IITM) contributes to the broad recognition of IITM as an internationally leading climate research institute and is instrumental in establishing fruitful cooperation of IITM scientists with the global community of climate researchers under the auspices of WCRP. The IITM is a premiere research institute of Ministry of Earth Sciences, Government of India and its' major vision is to make IITM a World Centre of Excellence in Basic Research on the Ocean-Atmosphere Climate System required for improvement of Weather and Climate Forecasts. With this vision it leads several national/international mission mode projects (e.g., Monsoon Mission: to improve dynamical prediction of Monsoon weather and climate; Center for Climate Change Research, CCCR; System of Air Quality Forecasting and Research, SAFAR; Cloud Aerosol Interactions and Precipitation Enhancement Experiment, CAIPEX).

The International CLIVAR Monsoon Project Office (ICMPO) at IITM, Pune is responsible for providing:

Support to the CLIVAR Research Focus on:
Intraseasonal, Seasonal and Interannual Variability and Predictability of Monsoon Systems, in close cooperation with the WCRP Grand Challenges on Regional Climate Information and Water Availability and all relevant WCRP modelling and other activities.

Support to CLIVAR panels:

- Monsoons Panel (joint with GEWEX)
- Indian Ocean Region Panel And for
- Liaison with all WCRP, and other international monsoon related activities, eg. MAIRS
- Production of CLIVAR Exchanges (Desktop Publishing)

CLIVAR Monsoons Portal:
The ICMPO is currently undertaking work to develop a Monsoons Portal that will be served through the Monsoons Panel website. The Portal will catalogue current monsoon research initiatives and projects, covering observations, process-studies, modeling, prediction, and links to applications. This will serve as a clearing house for information about these activities, including short descriptions, list of references, etc., facilitating the assessment of the state of monsoon research. Information and resources that are relevant for the international monsoons community will be assembled, for example news items, capacity development opportunities and information about meetings. There are also plans to develop a monsoons research network, widening the reach of information of, and increasing participation in, relevant CLIVAR/GEWEX initiatives.

Composition of ICMPO:

i. Dr. Rokkam R. Rao, Director

ii. Dr. Ramesh Kripalani, Senior Scientist (Part Time)

iii. Dr. K. P. Sooraj, Scientist (Part Time)

iv. Mr. Harish Jagannath Borse, D.T.P. Operator

Emerging challenges in advancing predictions of the North American Monsoon

David Gochis

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Introduction

Precipitation from the North American Monsoon (NAM) system provides critical water resources for Mexico, many Central American countries, several island nations in the Caribbean and parts of the southwest USA. Extreme rainfall and associated flooding events during the monsoon season, whether from local convective storms or land-falling tropical storms, form one of the most severe weather related risks to the region while, periodic drought, as a result of diminished monsoon precipitation, also can create widespread hardships that, historically, have been contributors to social and political unrest in the region. However, as in many monsoon systems around the world, the climate of the North American Monsoon (NAM) is dominated by strong spatial variability, punctuated episodes of heavy precipitation and strong seasonal and diurnal cycles of precipitation. Inter-annual variability of monsoon precipitation is also high, and in some places the standard deviation of seasonal rainfall exceeds 50% of mean seasonal precipitation (Gutzler, 2004). It is against the backdrop of these hydrometeorological and hydroclimatological features that significant work was undertaken to coordinate improved understanding and prediction of the NAM throughout the 1990s and 2000s (Douglas et al., 1993; Vera et al; 2004; Higgins et al., 2006).

From 2000-2010, a ten-year research program was coordinated to improve understanding and prediction capabilities within the NAM region, the North American Monsoon Experiment (NAME). NAME was conceived and endorsed by members of the CLIVAR and GEWEX communities to address fundamental shortcomings in the understanding of multi-scale processes controlling the behavior of the North American Monsoon (NAM) and its modes of variability that were thought to be limiting prediction skill of warm season precipitation. The tiered programmatic structure designed and implemented in NAME served to address key objectives of improving predictions of: **a)** the diurnal cycle of warm season convection in complex terrain (within the locus of maximum North American continental diabatic heating); **b)** intraseasonal variability of the NAM (and its associated linkages to synoptic & mesoscale transients); and **c)** seasonal and interannual cycles of NAM moisture convergence and rainfall patterns (e.g. Monsoon onset, mature, decay phases). A major Enhanced Observing Period (EOP – see Higgins et al., 2006 for a summary of the 2004 NAME-EOP) was conducted during the boreal summer of 2004 to provide important information on the processes driving NAM behavior. Collective works from NAME and since then have greatly expanded our understanding of the many of the multi-scale controls on monsoon behavior. The intent of this article is not to summarize the major research findings of these past programs but instead to highlight a few key recent findings that emerged from North American Monsoon research as well as identify an addressable set of remaining research challenges that can be addressed by a newly coordinated monsoon research effort under CLIVAR and GEWEX. The article finishes with a final statement on the need for improved collaboration and support mechanisms in order to transfer research effectively into national meteorological and hydrological prediction services.

Recent Findings

While several of the multi-scale controls on monsoon behavior have been elucidated, several outstanding questions still exist which are still greatly limiting our ability to produce skillful monsoon predictions across a range of time and space scales relevant for decision making, emergency preparedness and societal adaptation. Many of these questions center around how the seasonal and diurnal cycles of rainfall in the NAM region are and will continue to evolve in response to environmental changes such as a warming climate and continued land-use and land-cover changes. Of particular interest to CLIVAR and GEWEX is how fundamental exchange processes between the ocean and atmosphere and land and atmosphere, respectively, regulate both mean and variability structures of the NAM.

Prior research has documented how precipitation patterns and the occurrence of heavy rainfall episodes are strongly linked to orographic features and the proximity to coastlines (e.g., Cortez et al., 1999; Gochis et al., 2007; Nesbitt et al., 2008). More recently, it has been shown that statistically significant positive trends exist in extreme warm season rainfall events (95th and 99th percentiles) (Arriga-Ramirez and Cavazos, 2010).Part of the variability of trends in extreme precipitation are linked to natural variations resulting from the combined effects of El Niño/Southern Oscillation and the Pacific Decadal Oscillation (PDO) (Arriga-Ramirez and Cavazos, 2010). Many extreme rainfall events in the NAM region are associated with land-falling or near-shore tropical storms (Englehart and Douglas, 2001; Gutzler et al., 2013) which are themselves significantly modulated by air-sea interactions and large-scale SST patterns and their associated climate modes such as ENSO, the PDO and the extent of the western hemisphere warm pool (WHWP) (Enfield and Cid-Serrano, 2010; Perez-Morga et al., 2013). Despite this basic climatological understanding, there is uncertainty as to exactly how patterns of the WHWP, ENSO and PDO variability impact the frequency and intensity of land-falling tropical storm activity in all regions of the NAM (Farfan et al., 2013). For instance, Martinez-Sanchez and Cavazos (2014) have shown that while SSTs in the principle eastern Pacific tropical storm development region have increased by more than 0.5°C from 1970 to 2010 there have been no significant trends in major hurricane activity emanating from that region.

It is also unclear at present how ongoing trends in tropical SST will impact non-tropical storm precipitation the NAM region. It is hypothesized that differential trends in the heating of the oceans and the land surface may also have a significant impact on NAM precipitation. However, Torres-Alvarez et al. (2014), in an analysis of an ensemble of CMIP5 global models, showed that while the land-sea temperature contrast is projected to increase, changes in the regional, mid-tropospheric subsidence due to invigorated tropical convection may act to suppress convection in parts the NAM region (see also Arias et al. 2012). In particular, Torres-Alvarez showed that coastal regions with possessing weak convective triggering are projected to have less rainfall while interior and mountainous regions that possess strong, stationary internal triggers for convection are projected to see increases in precipitation (see Fig. 1). Changes in land-sea thermal contrasts are also projected to influence the timing of NAM onset and demise. However, continued biases in global models with respect to the amplitude of the seasonal cycle of monsoon rainfall as well as in the overall character (timing, intensity and frequency) of monsoon rainfall events may limit the credibility of such projections (Bukovsky et al. 2013; 2014).

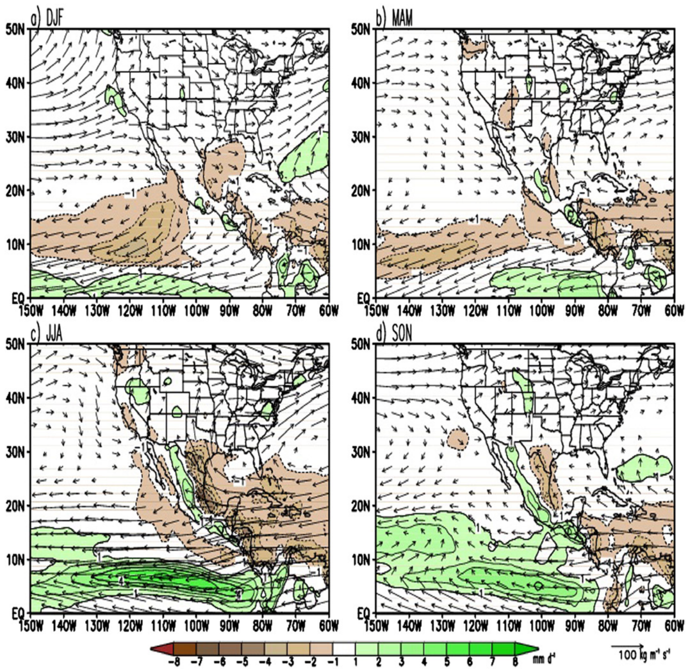

Figure 1 : Mean seasonal differences between an ensemble of RCP8.5 GCM projections (2075–99) and the historical period (1979–2004) for the vertically integrated moisture flux (vectors; kg m−1 s−1) and its convergence (shading; mm day−1). [From Torres-Alvarez et al., 2014, J. Climate.]

The role of terrestrial physiography and ecosystems in modulating land-atmosphere energy and moisture exchange is increasingly being recognized as an important control on the production of moist static energy, soil moisture and certain components of the monsoon climate (Dominguez et al., 2009; Notaro, and Gutzler, 2012; Xiang et al., 2014). Highly adapted vegetation communities in the region can withstand large variations in soil water availability during the growing season while not suffering dramatic changes in canopy conditions following initial seasonal leaf out. Such adaptations are difficult to represent in current models that use simplified biophysics parameterization that rely on climatological vegetation conditions. Additionally, unlike some other monsoon systems that exist on broad, flat, rolling terrain the NAM is characterized by a host of complex terrain features which in turn produce strong controls on patterns and time scales of soil water availability for evapotranspiration and surface energy flux partitioning as well as runoff production that feeds regional stream and river systems (e.g. Mendez-Barroso et al., 2014; Gochis et al., 2010). A major issue in understanding uncertainty in the spatial and temporal characteristics of land surface processes in the NAM region though has been a relative dearth of long-term observational facilities. Only within the last few years has research from sustained flux measurement sites in the core NAM region begun to provide quantitative estimates of energy and water flux terms that are important to understanding NAM variability (Vargas et al., 2013). There is also a critical need to be able to quantify the coupling strength between soil moisture and precipitation in the NAM region as a means to inter-compare NAM land-climate interactions with other monsoon systems around the world. While approaches doing such studies are traditionally model-based, the opportunity to confront such models with existing and new hydrometeorological observations would help constrain such estimates and therefore help elucidate NAM controls and feedbacks more systematically.

Current Challenges

As a new CLIVAR/GEWEX Monsoon Panel seeks to address the challenge of improving multi-scale predictions of monsoon behavior a host of questions arise that need to be addressed. While some of these questions reflect long-standing challenges in NAM research, others have only more recently emerged. Newly emergent questions often tend to involve multi- disciplinary research components outside of traditional physical climatology components and include topics such as ecosystem dynamics, atmospheric chemistry, agro-meteorology, water management and physical geography to the extent that we are able to characterize and predict changes land cover and land and water use practices. These challenges involve developing improved understanding and predictions of:

- Seasonal evolution of large-scale controls (e.g. Synoptic patterns and propagating disturbances including the ISV modes) versus local controls (e.g. Magnitudes and time-scales of land surface energy and moisture fluxes) on deep convection and drought within the monsoon region
- Cross-equatorial controls on large-scale patterns of subsidence and moisture transport between North and South America
- Tropical storm formation and evolution
- Changing dust and aerosol concentrations and their impacts on cloud and precipitation processes
- Future climate and land-cover/land-use changes and their impacts on NAM precipitation and patterns of hydrologic response (both flooding and drought)
- Societal mitigation and adaptation to projected changes in NAM precipitation and water availability

These issues extend beyond basic characterization of NAM features but require in-depth process-based investigation and, like the NAME program exhibited, whose address would ideally foster the development of sustained, jointly-coordinated observational-data assimilation-modeling studies. Addressing these questions will require fundamental and science-based improvements to research and operational observation and data assimilations in order to properly characterize sources of uncertainty and constrain model behavior.

Support of National Meteorological and Hydrological services

Finally, despite the scientific and technological advances that are occurring throughout the North American Monsoon region, significant challenges remain in transitioning such progress into operational forecast warning and guidance products issued from many national meteorological and hydrological prediction services. The causes for this 'research to operations' gap are manifold and include inadequate resources and infrastructure to support advanced observing systems, substantial high performance computing resources, weaknesses in telecommunication infrastructure and insufficient human resources. Certainly, pervasive gaps in seasonal prediction skill contribute to errors and uncertainties at longer lead time scales. These gaps are evidenced by the large disparities in extreme event impacts, particularly in terms of the loss of human life, between many countries and island nations under the influence of the NAM and the U.S. For GEWEX and CLIVAR to meet the WCRP Grand Challenges, deeper and more sustained collaborations between researchers and operational prediction centers throughout the NAM region must be forged and maintained.

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The South American Monsoon

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Introduction

The South American Monsoon (SAM) is an important component of the global monsoon system resulting from seasonal changes in the thermal contrast between continents and adjacent oceanic regions. Predicting the intensity of monsoon rainfall over South America is not only a regional challenge, but is also relevant in the framework of a global seasonal forecasting system. Most of the annual precipitation over most of South America occurs during the summer, including in subtropical regions. The economy, agriculture, water and energy resources and, consequently, the livelihoods of the great majority of South America population are heavily dependent on the summer monsoon.

It is worth pointing out that the worst energy crisis ever to hit Brazil (in 2001) and the very intense drought affecting Southeast Brazil (in 2014), were both associated with deficient summer precipitation. On the other hand, abnormally intense monsoon precipitation may induce flood, crop loss, and disease epidemics, with all the resulting social and economic consequences. From a public policy perspective, having reliable predictions of monsoon intensity prior to the monsoon onset could facilitate the implementation of policies designed to mitigate the negative impacts of adverse monsoon conditions. Thus, monthly or seasonal, medium- to long-range forecasting of summer monsoon rainfall is a scientific issue of great relevance and is a high priority for most of South America.

The presence of the Andes and the low-level jet to their east, the mountains in the eastern part of the Brazil and their effects on the South Atlantic Convergence Zone (SACZ), the local influence of Atlantic SST anomalies and the effects of remote SST anomalies, especially from the Pacific, combine to produce rich variability of the SAM. It is highly variable from both temporal and spatial points of view, with modes ranging from synoptic and intraseasonal to the inter decadal temporal scales (see the review papers Nogués-Paegle et al. 2002; Grimm et al. 2005; Vera et al., 2006; Grimm and Silva Dias, 2011; Marengo et al., 2012). Monsoon forecasting therefore requires the knowledge of this spatial and temporal variability and the understanding of a variety of complex mechanisms involved in this spatio-temporal variability. Beyond natural climate variability, in the context of anthropogenic climate change, South America could experience an increase in monsoon precipitation variability, with a possible increase in the frequency and severity of both droughts and floods (Kitoh et al., 2007), and the impacts of the natural variability itself could change (Grimm 2011).

The physical mechanisms that contribute to the existence of specific modes of SAM oscillations (synoptic, intraseasonal, interannual, inter decadal, etc.), Their interactions and the role of ocean-atmosphere and land-atmosphere feedbacks in these temporal scales are not yet clearly understood. Therefore, as a part of the broader effort to develop useful medium, extended or long-range predictions, the main mechanisms of intraseasonal to interannual variability, as well as the main surface-atmosphere feedbacks associated with ocean and land surface boundary conditions have to be examined in more detail, in both observations and coupled/forced simulations of the SAM. Forecasting skill can be achieved only by knowing the spatial and temporal variability of the monsoon and its associated precipitation.

SAM Variability

The wet season starts in the western Amazon in the austral spring (September) and then spreads to the south and southeast, reaching southeast Brazil in October. By late November, deep convection covers most of central South America from the equator to 20°S, but is absent over the eastern Amazon Basin and Northeast Brazil. During the mature phase of the SAM, from late November through late February, the main convective activity is centred over central-west Brazil, the SACZ is well established, and the convection is extended towards eastern Amazon. In March, the SAM weakens over most of the continent (e.g. Grimm et al. 2005). This climatological picture undergoes variations in several temporal scales. The SAM shows distinct peaks in the intraseasonal band at 10-20 day, 20-25 day and 30-70 day (e.g., Nogués-Paegle et al. 2000; Grimm et al. 2005). The origin of the intraseasonal oscillations in the two first bands is not completely understood and may result from internal atmospheric variability associated with the propagation of mid latitude disturbances into the region. The 30-60 day peak has been linked to the Madden-Julian Oscillation (MJO, e.g., Grimm and Silva Dias 1995; Nogués-Paegle et al. 2000; Carvalho et al. 2004). The MJO has significant impact on precipitation over different parts of South America in its different phases. This impact shows potential predictability (Jones et al. 2004). Its influence is caused by tropics-tropics and tropics-extra tropics teleconnections. For instance, the 30-70 day variability over the SACZ can be forced from the Pacific (Grimm and Silva Dias, 1995).

The main source of interannual variability of precipitation during the summer monsoon season is ENSO (Nogués-Paegle and Mo 2002; Grimm 2011). Its impact has strong regional characteristics and changes from the early to the peak monsoon season, suggesting the prevalence of regional processes of land-atmosphere and ocean-atmosphere interactions over remote influences during the peak summer season. There is a significant tendency towards an inverse relationship between spring and summer anomalies in Central-East Brazil and part of South Brazil, a relationship that itself undergoes inter decadal modulation. There is also strong inter decadal variability in the precipitation of the monsoon, in connection with regional or global SST variations (e.g., Nogués-Paegle and Mo 2002; Grimm and Saboia 2014).

There are significant relationships between the inter decadal variability in spring and summer, as in interannual time scales. The first modes for both seasons are dipole like, displaying opposite anomalies in central-east and southeast SA. They tend to reverse polarity from spring to summer. Yet the summer second mode and its related spring fourth mode, which affect the core monsoon region in central Brazil and central/northwestern Argentina, show similar loadings, indicating persistence of anomalies from one season to the other. The main modes show connections with more than one climatic index and more than one oceanic region, stressing the importance of combined influence. However, the main influence on the first mode seems to be the Atlantic Multidecadal Oscillation, while the second mode seems more connected to the Inter decadal Pacific Oscillation. This second mode describes the "climatic shift" of the mid 1970s.

SAM modelling, predictability, prediction and some challenges

Atmospheric, coupled and Earth system models represent well the main differences of summer and winter with respect to precipitation and atmospheric circulation in South America. The annual cycle of precipitation in the SAM core is also well simulated, although some models show underestimated or overestimated values. Some CMIP5 models have significantly improved their representation of the SAM relative to their CMIP3 versions, but there are still systematic errors of precipitation intensity in large areas of the monsoon system, including (i) excessive precipitation over northeast Brazil, (ii) displaced ITCZ (Inter-Tropical Convergence Zone), (iii) double ITCZ, and (iv) too little precipitation over the eastern Amazon near the river mouth (Jones and Carvalho 2013). Some aspects of SAM simulated by models are summarized in Cavalcanti (2013).

Suggestions to reduce such errors are: improvements in parameterization schemes of physical processes, and better resolution of topography and improvements of the diurnal cycle. Besides, some other aspects that should be improved to reduce errors in the SAM region are: clouds microphysics and clouds cover, clouds-radiation interactions, deep and shallow convection schemes, surface processes and their interactions with the atmosphere, boundary layer and soil moisture initialization.

Diurnal cycle of precipitation is an important issue. The atmosphere-land and atmosphere-ocean interactions depend on the correct representation of the diurnal cycle of variables in each system. Cloud cover has impacts on radiation, and feedbacks occur within this interaction, which depend on the proper simulation of diurnal cycle.

Soil moisture and vegetation are important land components for the SAM in numerical models. Temperature, humidity and momentum fluxes should be properly simulated in climate models. The simulation of the tendency to reversal of the sign of the precipitation anomalies from spring to summer in parts of Central-East Brazil might depend on the correct simulation of these aspects. As the SAM is influenced by Rossby wave trains (especially from the Pacific, such as the PSA-type) the models need to have a good representation of precipitation and variability in that region, including Indonesia and Australia. There are also interhemispheric features, multidecadal variability and Atlantic Ocean influences that should be simulated by the models.

Since specific humidity and wind components are variables better simulated than precipitation in numerical climate models, it may be better to use the prediction of atmospheric circulation and humidity features linked to the SAM, instead of predicting precipitation. For instance, the SAM onset and demise prediction could use indices that do not apply precipitation thresholds for the beginning and end of the rainy season (Gan et al. 2006; Raia and Cavalcanti 2008).

Scale interactions on seasonal, intraseasonal and diurnal time scales are sources of systematic errors in numerical models, as discussed by Slingo et al (2003), and should also be a topic of study, along with inter decadal, interannual and intraseasonal variability studies in climate models to assess the predictability over SAM region.

The general consistency of ENSO impact lends some predictability over South America on interannual time scales. Even so, there are uncertainties associated with the inter-event variability (Tedeschi et al. 2014), and this ENSO-related predictability is restricted to specific times of the year and certain regions (e.g., Montecinos et al. 2000). Furthermore, the influence of interactions between extra tropical modes and ENSO (e.g., Carvalho et al. 2005; Silvestri and Vera 2009) and inter decadal modes and ENSO (Andreoli and Kayano 2005; Grimm and Saboia 2014) on SAM are not well known. The influence of Atlantic SSTs is not well known either, except on Northeast Brazil, although recent research has demonstrated the modulation exerted by the tropical North Atlantic on the ENSO response (Mo and Berbery 2011). There might be some predictability on the decadal/inter decadal time scales, but this is still an open question. Although models reproduce some of the main characteristics of the ENSO impact on the SAM, they miss some important characteristics in the monsoon season variability. One is the tendency for a reversal of the sign of precipitation anomalies from spring to summer in parts of Central-East Brazil (Grimm et al. 2007; Grimm and Zilli 2009). However the models usually tend to show persistence of the anomalies in this region (Grimm, Zilli, and Cavalcanti 2007). This might account for part of the low performance of models in Central-East Brazil, including the SACZ, where the seasonal forecasts for austral summer precipitation have no skill (Cavalcanti et al., 2006). The summer precipitation dipole over South America, which represents the mode of variability of the SACZ, is well simulated by global and regional models. However, seasonal prediction on a scale of three to six month forecasts does not show skill in this region. Studies of predictability are needed, taking into account the tendency to reversal of anomalies from spring to summer, detected by Grimm et al. (2007).

The intraseasonal time scale shows relationships with quasi-periodic oscillations, such as the MJO, allowing some predictability in this band. Notwithstanding, there are other shorter intraseasonal oscillations that are not well understood and which interact with the MJO and may modify it substantially. The MJO representation in models has been a challenge, but improvements in models have shown the ability of predictions, as discussed in Rashid et al. (2011), and Seo and Wang (2010), among others. There are studies indicating that MJO activity increases predictability over South America (e.g., Jones and Schemm 2000; Jones et al. 2004). However, simulations of its impacts over South America still do not correctly reproduce their timing and spatial distribution. Further studies are needed to characterize this influence in more detail and verify it in model simulations and predictions.

Some research priorities and challenges

1. Regarding ENSO impact on the monsoon, there are still questions to be investigated, including how interactions between ENSO and extra tropical modes affect its impact on SAM, and how inter decadal variability affects the impact of ENSO and the transition from spring-to-summer precipitation?

2. How do extra tropical modes and mid-latitude/ extra tropical processes affect SAM? There are, for instance, indications

that the Antarctic Oscillation (or Southern Annular Mode) affects SAM on interannual (Carvalho et al. 2005) and inter decadal time scales (Grimm and Saboia 2014).

3. What are the different processes by which land-atmosphere interactions can influence the evolution of the SAM? How does their correct representation in models contribute to a better prediction on different time scales? There are indications that soil moisture anomalies influence the evolution of precipitation anomalies in different parts of SA in different ways (e.g., Grimm et al 2007; Collini et al. 2008; Sorensen and Menendez 2010). Besides, a clear understanding of the impacts of expansion of agricultural land, deforestation and afforestation on precipitation, and its mechanisms, is still lacking.

4. How predictable is SAM variability on intraseasonal, interannual, and inter decadal time scales? There are indications of predictability associated with the MJO, but models still have difficulty in simulating the correct timing/location of the impacts. There is skill in predicting the most consistent ENSO impacts, but this skill is restricted to certain portions of the ENSO cycle, and to certain regions. Besides, the relative influence of large-scale and local forcing mechanisms on the SAM needs further assessment. The prediction of inter decadal variability and its impacts on SAM is a major challenge that needs to be faced, since its impact is very significant (Grimm and Saboia 2014). Studies are needed to assess the predictability in different time scales, using results from CMIP5 and other experiments (including WCRP/WWRP THORPEX YOTC Task Force, WCRP/WWRP Subseasonal to Seasonal Prediction Project).

5. How important is the influence of the SAM variability on intraseasonal and interannual time scales on the variability of other monsoon systems, such as the South African monsoon? There are strong indications that this influence is significant (Grimm and Reason 2011). Therefore, it seems that the correct representation of the SAM and its variability in the models is not only important to SAM prediction, but also to prediction in other monsoon regions. On the other hand, how important is the correct representation of other tropical convective anomalies for the correct prediction of SAM?

6. What are the Aerosol-Radiation-Cloud effects due to fires in the Amazon and monsoon regions? They should be assessed based on modeling efforts supported by observational information.

7. What is the best way to develop a monitoring/information system to appraise the monsoon conditions preceding and during the summer crop growth season in a region that is among the largest food producers in the world?

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Key research and prediction challenges for West and Central Africa

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Introduction

Our understanding of the monsoon system of West and Central Africa, its modelling and predictability, have been highly improved thanks to AMMA, the main international programon climate and its environment in Africa. Substantial progress was made during the past decade through strong international coordination of African, European and US scientists, leading to the deployment of long-term observation systems from 2001, and more far-reaching field campaigns between 2005 and 2007, with several periods of intense observation. This hasled to an unprecedented multi-scale multidisciplinary database implemented in France and at Agrhymet in Niger. Following this first phase (2002-2009), AMMA is continuing with a further decade of research more strongly focused on the integration of weather and climate science with decision-making for the West African region. Together with end-users and decision-makers, AMMA aims at developing and improving tailored tools and products to cope with hydro-meteorological and climate hazards, and on enhancing capacity building and training efforts in the context of climate and environmental change. In terms of key prospects and challenges for research and prediction of the monsoon system of West and Central Africa, several issues are addressed below.

Weather Systems

The weak skill of climate and weather prediction models in capturing the characteristics of the West African monsoon, and more specifically its precipitation pattern and variability, motivates us to develop a better knowledge of the functioning of the system involving numerous couplings between the atmosphere, the continental surface, the ocean and aerosols, all through a multi-scale approach.

The skill at short forecast ranges depends on the quality of observations, models and data assimilation, but also on the theoretical limit to predictability in West Africa. The main difficulty in forecasting the synoptic activity over West Africa has its roots in the strong interactions between the easterly waves and convection, which are not properly represented by current models, especially during the triggering stage. AMMA contributed to reactivation and modernization of the radiosonde network (Parker et al. 2008) over West and Central Africa and provided complementary observations to document all components of this monsoon system. The assimilation of such improved observation networks and of alternative data such as satellite microwave channels over land (Karbouet al. 2010) significantly improves initial fields. However forecasts initialized from those improved analyses lose their advantage within the first 24hr of simulation.

Convection is very sensitive to the humidity field due to numerous nonlinear and small-scale processes that are not well represented in models (source of energy, surface fluxes, detrainment of convection, evaporation of precipitation generating convective wakes...). The difficulties are magnified over West Africa due to the dryer mean conditions and to the large variability of the humidity field characteristic of a semi-arid region. Cloud resolving models are now a powerful tool to study this coupling between easterly waves, convection and the surface, and to improve the representation of the key processes involved in weather prediction and climate models. During the last decade, a new generation of operational cloud resolving models has been developed, and the models are now able to properly resolve the life cycles of mesoscale convective systems, bringing new perspectives to forecast weather system over Africa (Beucher et al. 2013). Efforts must also be undertaken for quantitative physical understanding of remote influences on the West and Central African monsoon rainfall throughout the year to enable us to exploit inherent predictability. This addresses the triggering of easterly waves upstream of the West African region (Poan2013),the extra-tropical Rossby waves, the convectively coup led Kelvin waves,or the role of the low-level westerly jet off the western coast of West Africa (Pu and Cook 2010).

Intraseasonal variability

Three main modes of variability have been identified, two with a mean periodicity of 15 days called the "quasi-biweekly zonal dipole" over the Guinean Coast and Central Africa, and the "Sahel mode", and another with a mean periodicity around 40 days called the "African MJO" mode (Janicot et al. 2011). These modes have a regional scale and can strongly influence precipitation and convective activity, including monsoon onset. Their initiation and propagation are partly controlled by atmospheric dynamics, like convectively coupled Kelvin wave dynamics for the quasi-biweekly zonal dipole,teleconnections from the Indian monsoon for the MJO mode (Mohino et al. 2011; see Figure 1), or Saharan heat low ventilation processes induced by mid-latitude Rossby waves over the Mediterranean for the Sahel mode (Chauvin et al.2010, Roehrig et al 2011). Land–atmosphere and radiation–atmosphere interaction processes can also contribute to the maintenance and the westward propagation of the Sahel mode (Taylor et al. 2010). Extensive areas of wet soil associated with the positive phase of the Sahel mode induce weak surface heat fluxes and low-level anticyclonic circulation bringing moisture ahead of the convective zone and helping its westward propagation.

The African monsoon has a distinctive annual cycle with a rapid pole ward shift in peak rainfall between the coastal region and the Sahel at the end of June. Inertial instability has been invoked to explain this shift (Hagos and Cook 2007), but emphasis has also be given to the seasonally varying surface conditions over the ocean (specifically the establishment of the cold tongue) and over the land (including the evolving heat low).

To explore the potential forecast skill brought about by our advanced understanding of the intraseasonal variability,several initiatives have been launched to monitor the tropical intraseasonal variability in general and more recently with a focus on Africa (CPC,SUNY).

Among them, the MISVA collaborative project between Senegal and France aims at monitoring and forecasting the intraseasonal variability over Africa in real-time. This project has provided a series of diagnostic indices during the African monsoon season since 2011 and the experience has showed that dry and moist events can be detected several days in advance. In general such events are the result of the combination of several synoptic-to-intra seasonal modes. The physical understanding of the African monsoon helped to improve forecasting methods and led to the current writing of the "Forecaster's Handbook for West Africa" under the World Meteorological Organization umbrella.

The African monsoon from interannual to climate scales

At interannual time scales, anomalies in sea surface temperature (SST) in the Gulf of Guinea and the eastern Pacific are a dominant driver, as indicated by numerous observational studies, atmospheric global circulation models idealized experiments, and hind cast ensemble integrations (Giannini et al, 2005). That has spurred the development of several seasonal prediction systems. In many instances, the skill of the prediction is better for circulation variables (Ndiaye et al 2011), suggesting that a Model Output Statistics correction can lead to skilful rainfall prediction. It is possible that more skill will follow from incorporating a fuller range of external forcing including soil moisture.

A large fraction of rainfall variability in West Africa at decadal and longer time scales is also paced by variability in the SST (Giannini et al. 2003, Mohino et al. 2010). This has been related to the Atlantic Multidecadal Oscillation but anthropogenic forcing seems to have started to play a substantial role, in particular through anthropogenic emissions of sulphate aerosols in the Atlantic sector, which cause an inter-hemispheric pattern of SST anomalies (Ackerley et al, 2011).Local feedbacks can also operate. Aside the potential positive feedback of soil humidity and vegetation couplings with the monsoon system (Xue and Shukla 1993), an upward trend in the Saharan heat low temperatures has been observed during the partial rainfall recovery of Sahel rainfall over the last 20 years, due to greenhouse warming by water vapour, where changes in water vapour are strongly dependent upon the temperature of the heat low in a positive feedback process (Evan et al. 2014).

Climate projections of annual-mean Sahel rainfall for the end of 21st century are uncertain even in sign in both CMIP3 and CMIP5, but the seasonal evolution of the anomalies and their spatial pattern, are less uncertain (Biasutti, 2013). Dry anomalies in the first half of the year indicate a later beginning of the rainy season, while wet anomalies in September and October suggest a strengthening and concentration of the rainy season. This is consistent with circulation anomalies forced by a strengthening of the Saharan heat low.

A strong SST bias persists in CMIP5 simulations of the eastern tropical Atlantic, affecting the ability to predict interannual to decadal tropical Atlantic variability as well as climate change (Fig.2; Roehrig et al. 2013). The comprehensive set of AMMA observational data allows an in-depth evaluation of the African monsoon system modelling, especially through the use of high-frequency CMIP5 models outputs at selected sites along the AMMA transect. The simulation of the top-of-atmosphere and surface energy balances, in relation with the cloud cover, dust content, and the intermittence and diurnal cycle of precipitation demand further work to achieve a reasonable realism. Over the ocean, AMMA is supporting the implementation of new experimental campaigns for studying the key processes that relate to evolution of the Atlantic cold tongue thanks to the new EU FP7 PREFACE project (2013-2017).

Land-atmosphere coupling

On shorter time scales, the region was identified as a hot spot of soil moisture – precipitation coupling (Koster et al 2004). Rainfall variation on these scales controls soil moisture, in turn affecting fluxes of sensible and latent heat, and the properties of the planetary boundary later. Driven by strong spatial variability in rainfall, soil moisture can thus feed back on the atmosphere at scales from a few to 1000s km. AMMA Observations identified low level convergence induced by mesoscale gradients in soil moisture (Dixon et al 2012) and vegetation (Garcia-Carreras, 2010). Various atmospheric modelling studies have shown the importance of soil moisture patchiness on these circulations and their role in the initiation of deep convection (Gantner and Kalthoff 2010, Birch et al 2012). Analysis of initiation of over 3000 mesoscale convective systems (MCS) provided a firm observational basis for this effect (Taylor et al 2011), showing a clear preference for the initiation of the first deep convective cells on strong soil moisture gradients induced by rain in previous days. As a result of this feedback, rain from MCSin their early stages is more likely over drier soil, but may shift to heavier rain over wetter soil in some circumstances.

Many challenges remain for modelling the land surface influence on the atmosphere in West Africa. Surface processes are often poorly described (e.g. Rapid vegetation phenology) or ignored (ponding and interaction with groundwater). Current convection schemes in large-scale models tend to be over-sensitive to surface evaporation, erroneously favouring daytime rain over wet soils, in contrast to convection permitting models (Taylor et al. 2013). This is of particular importance in the Sahel, where soil moisture controls on convection are especially strong, and convective variability plays a key role in the overall monsoon. The direct effect of poorly simulated seasonal evolution of precipitation on land fluxes was highlighted by Boone et al (2010), who illustrated the diversity of meridional gradients of surface sensible and latent heating in an ensemble of atmospheric general circulation models. These biases can in turn feed back on circulation. In terms of future climate, changes in land use may play an important role (Paeth et al 2009) though these are highly uncertain. Even without changes in land use, Sahelian vegetation is likely to change in the coming decades in response to rising temperature and CO2 levels, and in particular, to potentially large fluctuations in precipitation. These land feedbacks, combined with remote climatic forcing, make the provision of future climatic projections in the Sahel particularly challenging.

Coupling with aerosols

The African monsoon interacts closely with the largest dust source on Earth, the Sahara and Sahel. Multi-scale circulations and convection associated with the monsoon can lead to dust emission and transport (Knippertz and Todd 2012); in turn, dust modulates the long wave and shortwave radiation budgets, and can affect cloud microphysics through its role as ice and cloud condensation nuclei. Over the Sahel, the sign of the precipitation response to dust appears to follow the local top of atmosphere radiative forcing, which is sensitive to dust optical properties, leading to gross differences among modelling experiments (Yoshioka et al. 2007, Solmon et al. 2012).

During summer, dust storms can be caused by nocturnal low-levels jets associated with flow acceleration into the Saharan heat low. Strong dust-lifting winds also occur at the leading edge of cold pools created by evaporation of precipitation from convective storms ('haboobs'), mostly over the Sahel and southern Sahara. Haboobs are difficult to detect from space due to the association with convective clouds and hard to model due to the difficulties with representing cold pools and mesoscale convective systems in models with parameterised convection (Marshamet al. 2013, Heinold et al. 2013).

Recent high-resolution modelling studies have shown that nocturnal low-levels jets can form within aged cold pools, thereby creating a strong link between convective activity, flow acceleration into the heat low and dust emission (Heinold et al. 2013). An additional factor relevant for dust emission is dry convective mixing in the daytime planetary boundary layer, which can lead to the formation of dust devils or dust plumes, which are not resolved in current dust models.

A major limitation to our understanding of the mechanisms of dust production in the Sahara is the lack of observations from this vast and uninhabited region.Long-term station records are mostly restricted to the Sahel. The AMMA Sahelian dust transect with three stations in Senegal, Mali and Niger generated an extremely valuable record over several years (Marticorena et al. 2010).

More recently, the UK Fennec project has for the first time provided very detailed observations from the central Sahara through the deployment of automatic weather stations in remote parts of Mauritania and Algeria, as well as research flights with the UK BAe146 and French Falcon.In order to better understand the complex interactions between atmospheric dynamics, aerosols, cloud and chemistry, and to complete the geographical coverage southward by including Southern West Africa,AMMA is supporting the implementation of new experimental campaigns thanks to the new EU FP7 DACCIWA project (2014-2018).

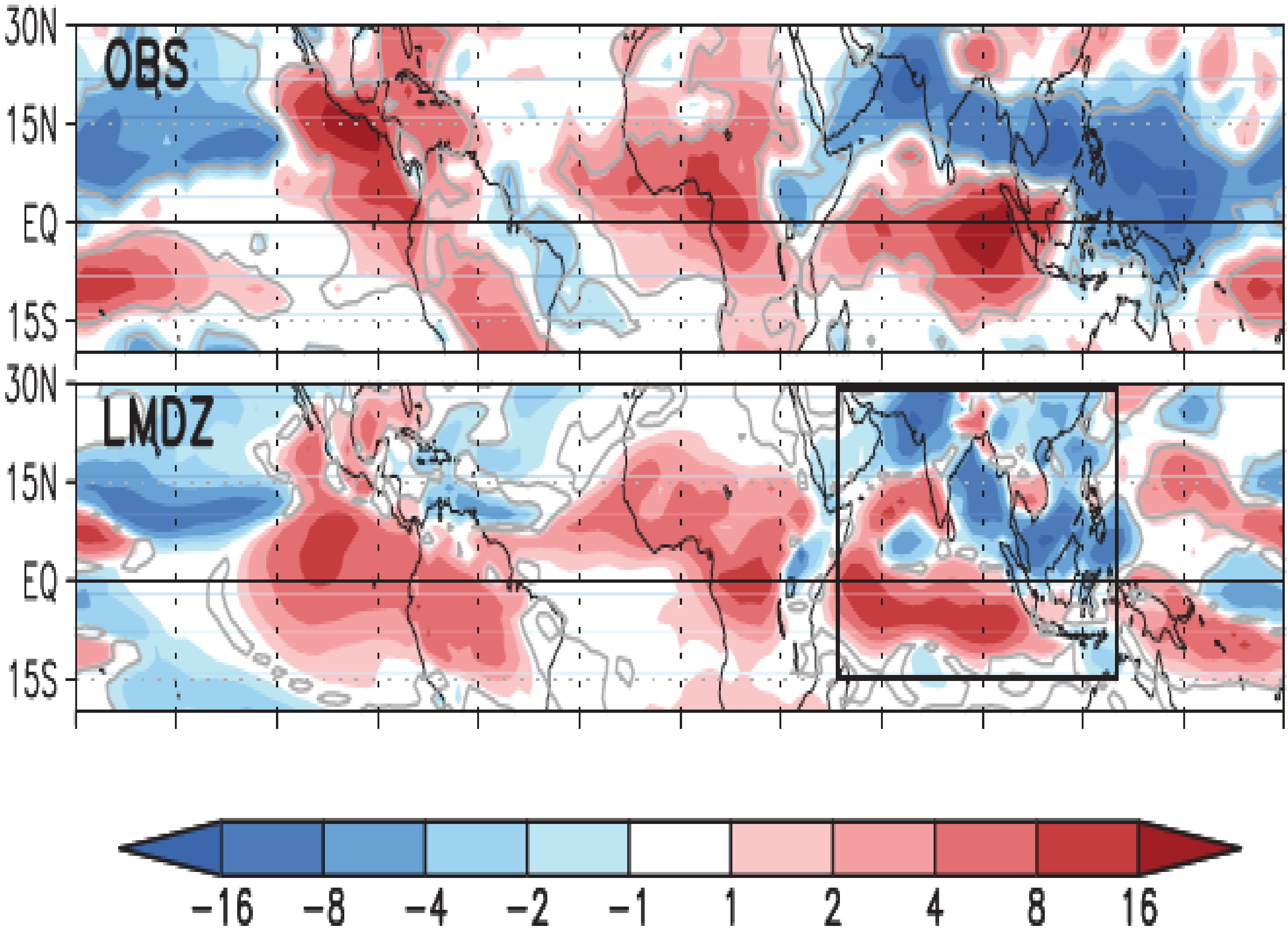

Figure 1: OLR anomalies present in observation and simulation, showing that the Indian monsoon intraseasonal variability has a significant impact on African monsoon convective activity. Top panel: 1979-2008 summer composites of observed deseasonalized anomalies of OLR (Wm-2) according to the active phase of the MJO signal over India (phase “8”). Grey contours mark 95% significant regions (according to a one sample test). Bottom panel: Same as bottom but for OLR simulated by the LMDZ atmospheric model relaxed toward reanalyses in the box domain.

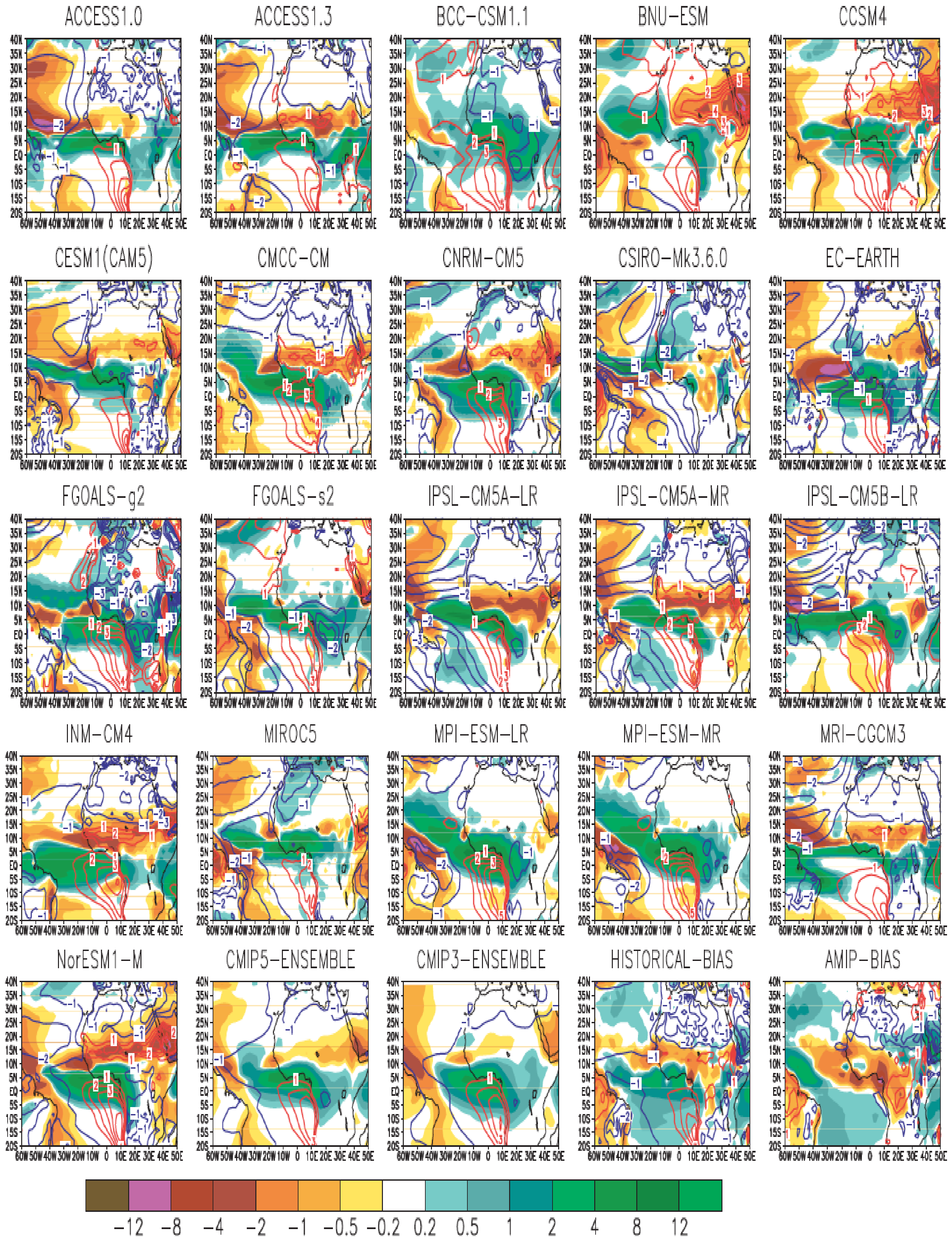

Figure 2: Difference between historical and AMIP simulations for precipitation (shaded, mm.day-1) and 2-m temperature (contours every 1K with the 0 contour omitted) averaged over the JAS seasons of the 1979–2008 period. The CMIP3 and CMIP5 ensemble means are shown in the bottom row, as well as the CMIP5 ensemble mean biases of historical and AMIP simulations against the GPCP dataset for precipitation and the ERA-Interim dataset for the 2-m temperature.

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Decadal Variability of the East African Monsoon

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Introduction

The East African rainy seasons are mainly associated with the passage of the inter-tropical convergence zone (ITCZ) of the northeast (NE) and southeast (SE) monsoons, following the inter-hemispheric migration of the overhead position of the Sun (Nicholson 1996; Leroux, 2001). The Long Rains (March to May) account for the largest proportion of the annual rainfall. East Africa has been experiencing a persistent decline of the Long Rains for multiple decades (Lyon and DeWitt, 2012).We have shown that the recent multi- decadal decline in rainfall is a result of the combined contribution of the Indo-Pacific and Atlantic Oceans, the latter connection previously unrecognized.

The Hydroclimate project for Lake Victoria (HyVic) is a Regional Hydroclimate Project (RHP) being developed under GEWEX (Semazzi et al., 2013; 2014). The primary purpose of HyVIC is to expand our understanding of the climate over the Lake Victoria Basin (LVB) and improve its predictability and projections to support regional decision-making. HyVIC has two domains: the Core Domain covering the LVB catchment; and the HyVIC Greater Domain covering the East Africa Monsoons region (EA outer domain, Figure 1), which modulates the lake basin-scale hydroclimate of the core domain. Both anthropogenic-driven global warming drivers (Williams & Funk, 2011; Lott et al., 2013) and natural sources of variability including the Pacific Decadal Oscillation (PDO) and ENSO-like Decadal (ENSOD) Pacific SST oscillation (Lyon, 2014; Omondi et al., 2013; Tierney et al., 2013; Yang et al., 2014) have been proposed to explain the recent multi- decadal drop in the Long Rains. Yet surprisingly the Atlantic Multi- decadal Oscillation (AMO;Del worth and Mann, 2000) has not featured prominently in this context. It is well established that the AMO plays an important role in modulating the decadal variability of the Indian Monsoon (Zhang & Delworth, 2006; Goswami, et al., 2006, Luo et al., 2011).

Thus we must take into account Atlantic drivers that previous studies have shown to account for the decadal variability of the Indian Monsoon. The focus of this study is to clarify if and how the Atlantic Ocean modulates decadal variability of the Long Rains and in particular their persistent decline.

We partition East Africa into three regions (Figure 1) to clarify this partial sensitivity of their relationships to drivers of decadal variability. To account for observational uncertainty, we used two recent versions of Climate Research Unit (CRU) data, TS3.21and3.22 (Harris et al., 2014),and the Global Precipitation Climatology Centre(GPCC; Rudolf et al., 2011) data. The rainfall data were subjected to a 10-year filter (Nadaraya, 1965) to focus on the multi- decadal time scale. Empirical Orthogonal Function (EOF) analysis was performed for the coastal, Nile, equatorial and the combined region in Figure 1 to isolate the dominant modes of decadal variability.

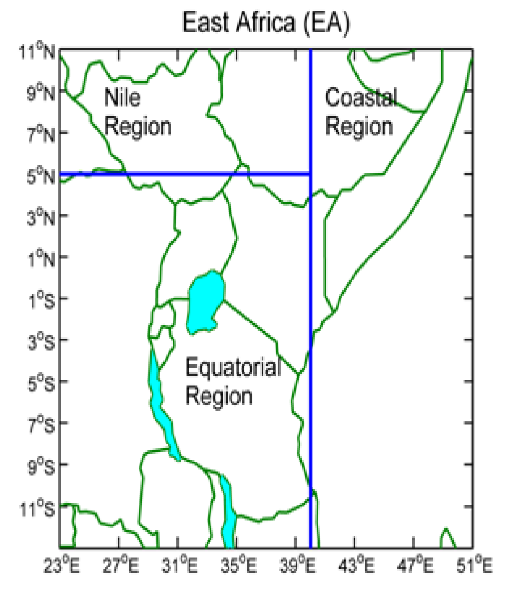

Figure 1: The primary domain (East Africa, EA) and its partition into the Equatorial, Coastal and Nile regions.

Results

Comparison of the rain fall are averages for the East Africa (EA) domain (Figure1) indicates both versions of CRU and GPCC following 1950 produce similar results. The strength of the relationship between the regionalising modes and the PDO or AMO climate indices (based on correlation) varies considerably across East Africa. Both the decadal variability for the Nile and the coastal regions are more strongly correlated with the AMO than PDO. However, decadal variability for the equatorial and the combined EA region (EOFs 1 and 3 respectively) are strongly correlated with both PDO and AMO. Furthermore, the composite SST pattern (not shown) constructed using the EA region EOF-2 time series is consistent with the SST (ENSOD) pattern found in Yang et al. (2014). Therefore we refer to the leading three MAM EA modes as: EOF1 PDO-related, EOF2 ENSOD-related and EOF3 AMO-related modes.

Rain fall data for the EA domain has been reconstructed by retaining the desired combinations of EA spring (MAM) rainfall from the EOF1PDO-related mode, E OF 2ENSOD-related mode and the EOF3AMO-related mode. Figure 2(left) suggests the contributions of PDO and AMO had the same sign since the early 1980s and therefore led to the intensification and persistent decline in the Long Rains. The ENSOD-related mode (EOF2) makes an insignificant contribution to the area average even though it explains larger variance than the AMO related rainfall mode (EOF3). However Figure 2 (right) shows that the ENSOD mode is important on the sub-regional basis, but not in the context of the regional East African area average.

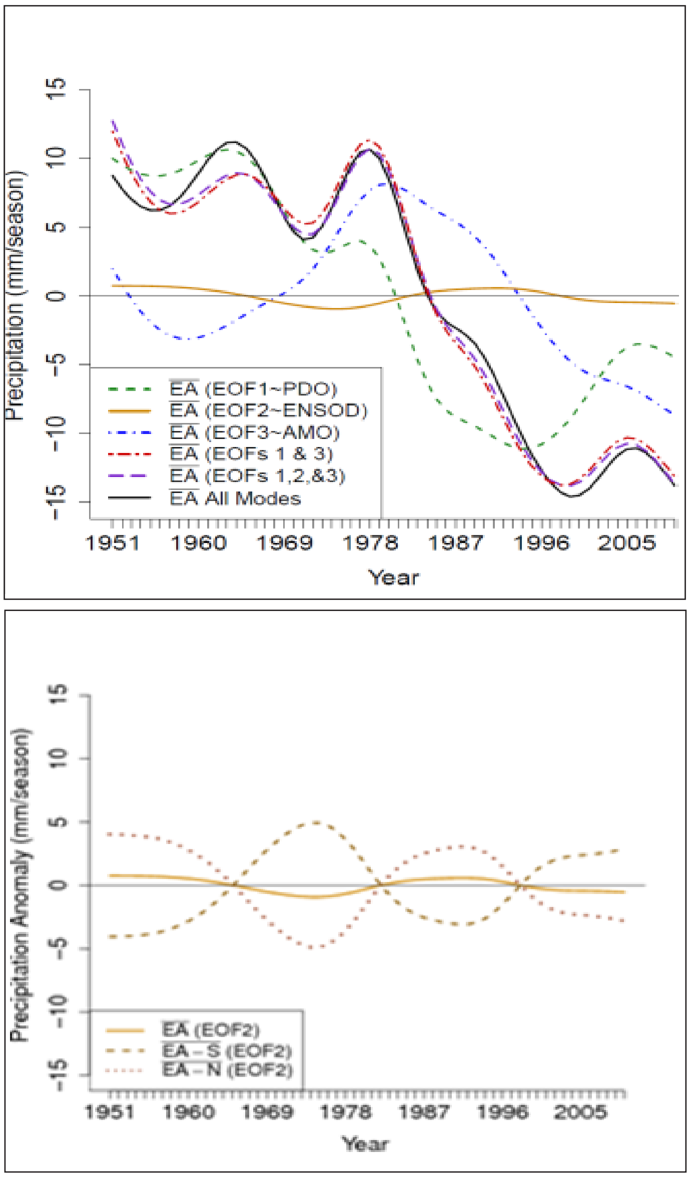

Figure 2: (Top) EA reconstructed rainfall area averages based on different combinations of EOFs (Bottom) area averages for the EA-south, EA-north and EA reconstructed rainfall based on EOF2. EA-south and EA-north are each about half of the domain and separated by along the 1 degree South latitude.

We investigated teleconnections between the Long Rains and Atlantic AMO by applying weighted compositing of the normalized reanalysis geopotential height data (Dee et al., 2011) at 300hPa based on the rain fall EOF time series for the EA region. We obtained EA EOFs separately for each month (March, April and May) of the Long Rains instead of the entire season as the calculations for Figure2; for March and April the AMO-related mode ranks fourth in explained variance, but is the leading mode (EOF1) for May during the cessation of the Long Rains. Therefore, we focus on the May EAEOF 1 mode instead of the MAM EA EOF3 mode to obtain a clearer signal of AMO influence on the Long Rains. For the negative phase of AMO, Figure 3 shows a distinct tropical stationary Ross by wave across northern Africa at3 00hPa and a high latitude stationary wave, both originating from a common North Atlantic source.

The high latitude stationary wave roughly tracks the northern coastline of Eurasia, consistent with Luoetal. (2011),which they associated with the variability of the

Indian monsoon. The tropical stationary wave is likely to be important in explaining the teleconnections between the Atlantic AMO SST a anomalies and the East Africa Long Rains.

The opposite anomaly pattern between the Indian peninsula and East Africa is consistent with the strong correlation found between cessation timing for the Long Rains and onset of the Indian Monsoon (Camberlin et al., 2010).Yet caution should be exercised to avoid attribution of this behavior based solely on geographical proximity. Figure3 suggests another important contribution characterized by an upper-level meridional jet-like current centered about 30°E due to the combined quasi-geostrophic motion around the Arabian geopotential height minima and the adjacent maxima along the wave axis. This extends over a deep layer of the troposphere and it is evident down to at least 700 hPa (not shown). This flow appears to converge around 12°N, consistent with the southern edge of a broad region of subsidence (not shown). Its northern source region coincides with the Mediterranean Sea, which could be an important conduit for moisture transport to East Africa during the Long Rains.

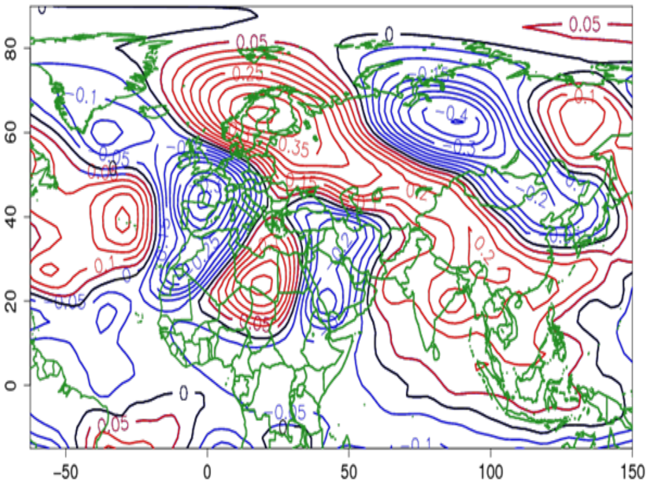

Figure 3: May EA rainfall EOF1 (AMO-like mode) composite (negative AMO phase) for geopotential and wind anomalies at 300hPa.

Discussion

Over the Nile region during the negative phase of AMO (Fig.4), the primary response appears to be determined by the upper level jet-like flow from the Mediterranean region (Figure3) of the tropical stationary wave that converges over East Africa. This leads to descending motion consistent with suppressed rainfall (Figure 4) over the Nile region. We propose a set of synoptic-scale factors that may account for the response of the Long Rains (Figure 5) to Atlantic AMO SST anomalies.

Over the coastal region, rainfall is enhanced during the negative phase of AMO due to the deflection of moisture-laden south-easterlies (Figure 5) away from the equatorial region towards the coast. The increased horizontal moisture flux convergence and the favourable conditions associated with the Arabian geopotential minimum could explain the positive rainfall anomaly pattern. Finally, over the equatorial region, southeasterly winds are deflected north towards the Ethiopian coast induced by the Arabian geopotential minimum depriving the region of moisture and resulting in negative rainfall anomalies. During the positive phase of AMO, the patterns essentially reverse. Considering the high correlation known to exist between the cessation of the Long Rains and the onset of the South Asia Monsoon, the tropical stationary wave connection found in this study may also have important implications for multi- decadal climate variability of the latter.

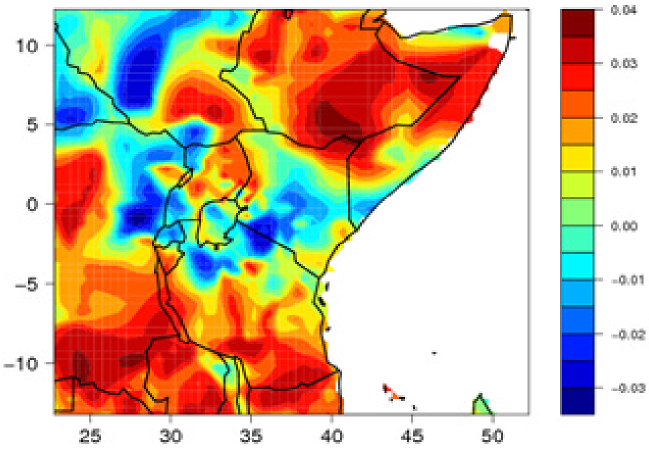

Figure 4: Rainfall May EOF1 loading for the EA region.

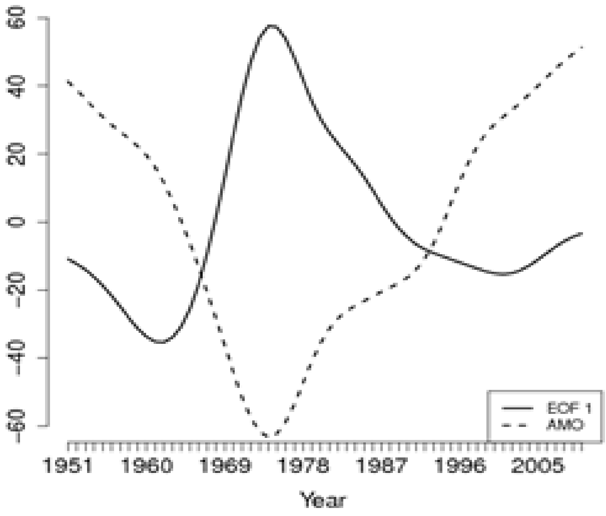

Figure 5: Rainfall EOF1 for EA region and AMO time series.

The observed tropical stationary wave train may have implications for dynamical down scaling climate modeling studies. It could be a challenge for the current Coordinated Regional climate Down scaling Experiment (CORDEX) model domain to represent the tropical stationary wave realistically since it is likely to be degraded by the northern model boundary. A shift of the northern boundary may be advisable for the next generation of the CORDEX models. Cook and Vizy (2013) have applied such an expanded domain in their study and report that over eastern Ethiopia and Somalia the rains are cut short in the mid-21st century because of anomalous dry anticyclonic circulation that develops over the Arabian Peninsula and northern Arabian Sea. It would be instructive to determine if the anticyclonic anomaly conditions they report are related to the Atlantic-induced stationary wave pattern we have found.

Figure 6 Schematic showing the hypothesized synoptic-scale factors that determine the response of the East African Long Rains to the tropical stationary wave. Climatological wind vectors in May are shown in the background

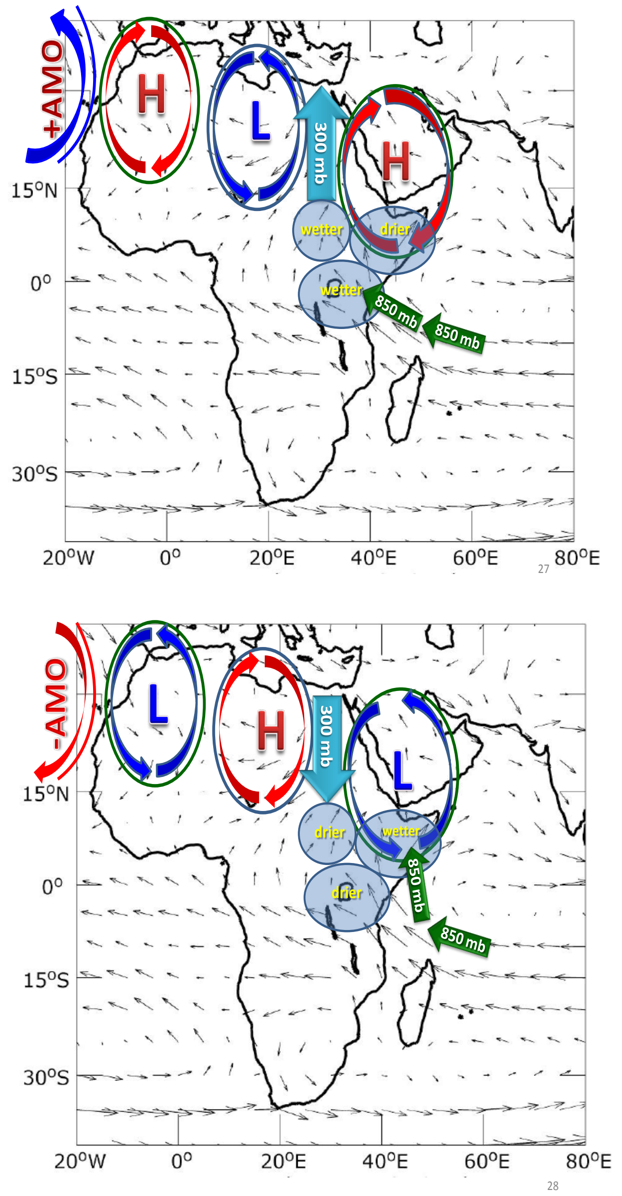

Figure 6: (Top) positive AMO phase and (Bottom) negative AMO phase.

Recommendations for there search community

We have presented a framework for diagnosing the relationships between dominant modes of decadal climate variability of the East African Long Rains and the leading global drivers of decadal climate variability. The connection between the East Africa and South Asian Monsoons noted here should is investigated further through the collaboration of the two international research communities working on these areas. Our frame work may be useful in future studies for evaluating CORDEX, CMIP and other model projects for East Africa.

The increased focus of CLIVAR on the monsoons, exemplified by the recent relocation of the International CLIVAR Monsoons Project Office to Pune in India, is a good opportunity for the strengthened Indoasia-Africa research collaboration. The continuing search for the attribution of decadal variability and a desired improvement of the climate projections for East Africa can benefit by pursuing several outstanding questions suggested below.

Climate Monitoring: What is the uncertainty among the gridded rainfall data sets (GPCC, CRU, etc.) for East Africa in representing the relationships between the East African Monsoon and the dominant modes of natural decadal variability? What observations are required to monitor the phenomena? How can multi- proxy high-resolution palaeo-records be applied to extend the record of PDO, AMO and ENSOD beyond the instrumental record?

Regional Processes Studies: How does climate change-driven response over East Africa interact with natural decadal variability? What are the regional physical mechanisms over East Africa that determine the regional response to remote sources of decadal natural variability and how well do we understand them ? What are the mechanisms over the Atlantic heat source region that determine the initiation and maintenance of the Atlantic AMO-Africa Ross by decadal wave train?

Model Evaluation: How well do we understand the response of the East African monsoon in models (e.g., Linear models, CMIP, CORDEX, etc.) to natural variability drivers including PDO, AMO and ENSOD?

Acknowledgements

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Persistence of Systematic errors in the Asian-Australian monsoon Precipitation in climate models: a way forward

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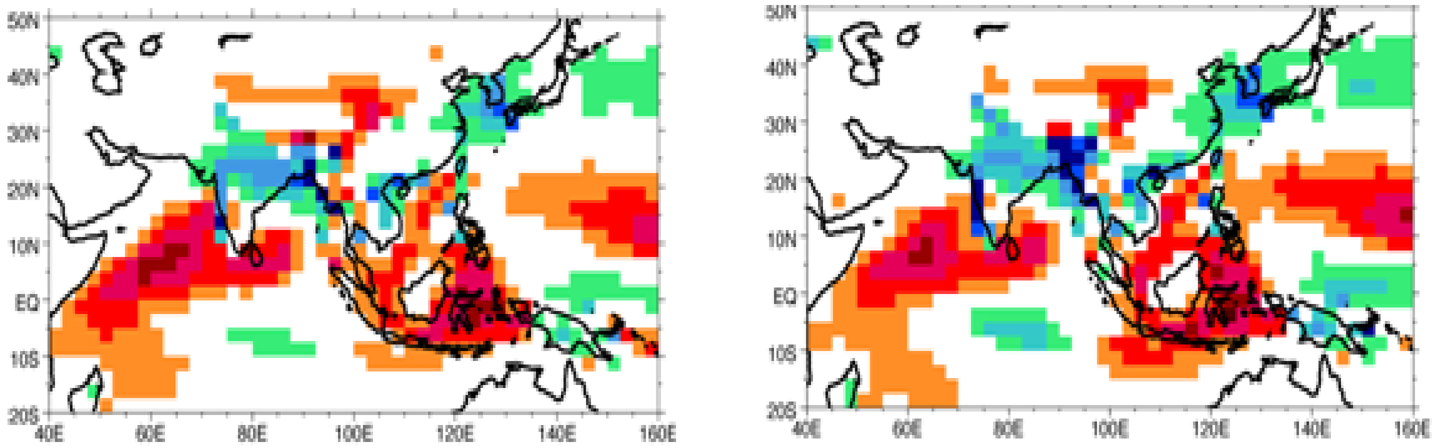
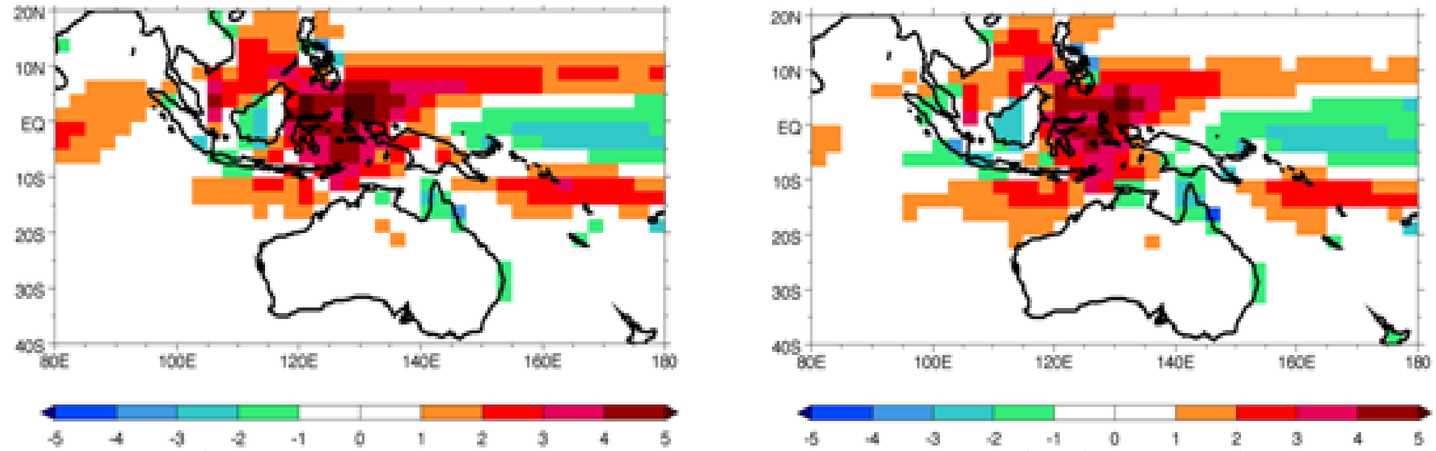
Introduction

The annual cycle of the Asian-Australian monsoon (AAM) system can be regarded as the seasonal displacement of the large-scale Inter-tropical 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 diabetic heating associated with the AAM is perhaps the most vigorous of all the regional monsoon components across 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.



(a) CMIP5 MMM minusObs (b) CMIP3 MMM minus Obs



(c) CMIP5 MMM minus Obs (d) CMIP3 MMM minusObs

Figure 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 Figure 1,the multi-model mean (MMM) errors for summertime precipitation relative to GPCP observations have shown little improvement in CMIP5 when compared to CMIP3 (Sperber et al., 2013). It is suffice to mention that 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 diabetic heating (Q) associated with the AAM influences the global circulation (Sardeshmukh and Hoskins, 1988). Figure 2 shows the vertical profile of Q, area-averaged over the South Asian monsoon region (5°–25° N, 60°–100° E) during boreal summer from CMIP5 models (Cherchi et al.,2014). Compared to reanalysis (solid black line), many models tend to have a maximum in 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% of the Q intensity (Schumacher et al., 2004). Independent observations from surface-based radars at Kwajalein site confirm stratiform contributions to total rainfall (Schumacher and Houze 2000). While partitioning of convective and stratiform rainfall, to certain degree, depends on the definitions employed, most of the CMIP3 models produce too much convective rainfall (Dai, 2006). Given the persistence of errors (Figure 1),we speculate that errors in the partitioning of total rainfall into convective-strati form still persist in CMIP5, and may be one of the reasons for underestimation (overestimation) of Q in the layer 600–300 (900–700) hPa.

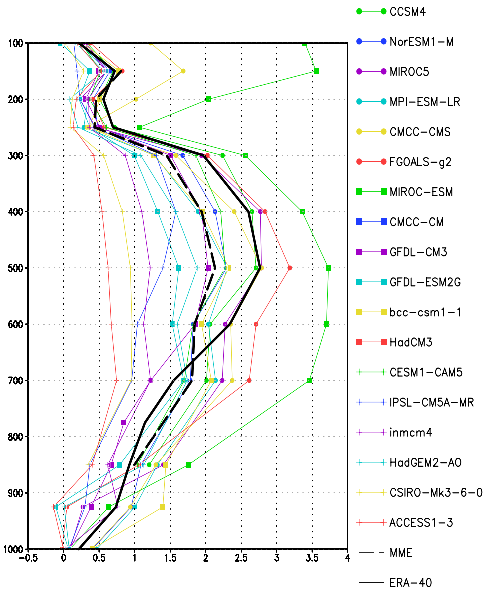


Figure 2: Vertical distribution of Q (K/day) estimated from CMIP5 and ERA reanalysis (solid line). The multi-model-mean composite (dashed line) is also shown (adopted from Cherchi et al. 2014)

In summary, the rather slow progress in modeling in the last decade has led us to wonder:

Has the scientific community reached a "plateau" in modeling mean monsoon precipitation?

The way forward

It is now recognized that the AAM is a fully coupled ocean-land-atmosphere system that is also influenced by 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 multinational research funding is the only way forward. Our focus here, 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 utilizea coupled ocean-atmosphere-land model that does develop a realistic, basic state. Figure 3 shows precipitation and SST climatology during boreal summer from satellite-based observations (Figure 3a) and a solution to a coupled model (Figure 3b), namely the Coupled model for Earth Simulator (CFES; Komori et al., 2008). Though not perfect (e.g., the reduced precipitation over the tropical western Pacific), the solution realistically captures the spatial distributions and amplitudes of SST and rainfall over South Asia and the tropical Indian Ocean that other models miss. 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 inter-monsoons on the precipitation climatology (Annamalai et al. 2014; manuscript submitted), finding that the systematic precipitation errors noted in CMIP5 (Figure 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

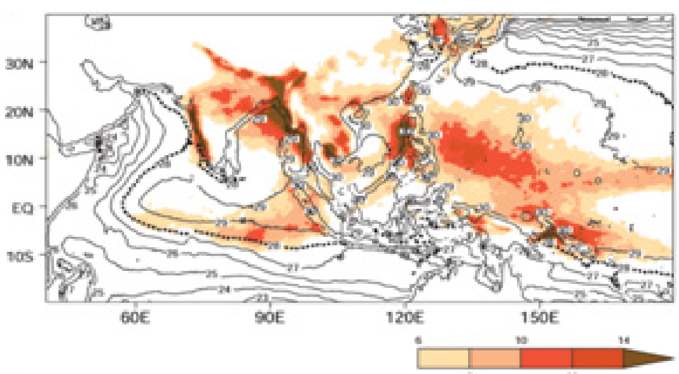


Figure3(a): Seasonal mean (JJAS) climatology of precipitation (mm/day; shaded) and SST (oC, contour): Satellite-based observations

(b)CFES

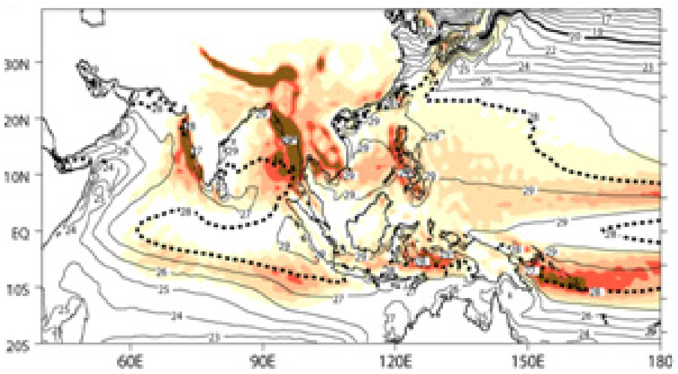


Figure 3(b): Coupled model for Earth Simulator (CFES). Only precipitation regions experiencing 6 mm/day and above are shown. The 28^{o}C is other m is shown as heavy dotted line.

(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, Figure 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)? Figure 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 3D 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 parameterization employed in the reanalysis system, model biases are more severe in global reanalysis in the

the data-sparse region of the AAM. Moreover, direct radiosonde observations of thermodynamic variables are subject to significant biases (perhaps due to outdated instruments), which reanalysis systems may not consider. It has been suggested that convergence of results from the different reanalysis products leans toward the "truth,"but maybe that convergence occurs for the 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 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., Derby shire 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 3D atmospheric states throughout the annual cycle along the AAM troughs 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 parameterization.

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 parameterization.

The Indian Ministry of Earth Sciences (MoES) has launched the 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 (Figure 1), cold SST bias also persists over the northern Indian Ocean in CMIP3/5 models (e.g., Levine et al., 2013), may be 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.

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 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. 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. Large investments are required for acquiring sustained high-quality observations. A coordinated effort among the international scientific community is needed to approach different funding agencies to make progress in this very challenging and highly demanding endeavour. We hope to pursue that effort in the coming years.

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A review of recent progress on Tibet's role in the South Asian monsoon

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Introduction

The Tibetan Plateau exerts a profound influence on winds in boreal winter primarily through mechanical means, blocking flow to create waves in the jet stream that extend around Earth's full circumference (e.g. Held et al., 2002). In contrast, this plateau was thought to influence boreal summer winds primarily through its thermal effects, providing a heat source over 4 km high and 2,000 km wide that generates the interhemispheric flow of the South Asian monsoon. But recent work has shown that although orography greatly strengthens the South Asian summer monsoon, it operates via a different mechanism that requires only a relatively narrow but continuous chain of mountains around the northern edge of the monsoon, rather than a broad plateau. This review presents a brief history of research on the role of orography in the South Asian summer monsoon, with a focus on recent work that frames monsoon dynamics in terms of modern theories for precipitating large-scale circulations. This review does not address the mechanical forcing by orography that seems important for East Asian climate (e.g. Wu et al., 2007; Wang et al., 2008; Molnar et al., 2010; Park et al., 2012).

1) Classic view of Tibet as an elevated heat source :

The rapid geographic expansion of Chinese meteorological observations in the 1950s pro- vided the first view of the Tibetan Plateau as a heat source for the boreal summer troposphere. Estimates of the atmospheric heat budget showed that the plateau must emit abundant sensible heat in boreal summer, sufficient to warm much of the overlying troposphere by about 2 K day−1 (Yeh et al., 1957; Staff Members of Academia Sinica, 1958). Together with the existence of a warm upper-tropospheric anticyclone in the vicinity of Tibet, these estimates were taken as evidence that direct heating of the middle to upper troposphere by plateau surface fluxes forced a large part of the South Asian monsoon (e.g. Koteswaram, 1958).

However, it was soon realized that condensation and precipitation of water just south of the plateau instead constituted the dominant diabatic heat source for the South Asian monsoon; the plateau's sensible heat fluxes were argued to indirectly drive the monsoon by causing this latent heating (Flohn, 1968). In other words, Tibet was claimed to be part of a "heat engine", with its sensible heating causing ascent and horizontal moisture convergence, that in turn produces the latent heating that drives monsoon flow. Decades later, Li and Yanai (1996) used gridded analyses of observations to confirm that diabatic heating by precipitation over the Bay of Bengal is the dominant heat source in the South Asian monsoon, and this diabatic heating is balanced by adiabatic cooling in the ascending branch of the monsoon circulation.

This balance between moist convective heating and adiabatic cooling due to ascent is a general characteristic of tropical circulations (e.g. Sobel and Bretherton, 2000), and makes inferring the causal heat source difficult because any net temperature change results from the small residual of large opposing terms in the thermodynamic equation. Nevertheless, Li and Yanai (1996) argued that observations of large sensible heat fluxes over the plateau supported "the thermal influence of the Tibetan Plateau as a dominant factor driving the planetary-scale monsoon system".

Numerical modeling studies provided what seemed to be support for that conclusion by showing that the intensity and pole ward extent of the South Asian summer monsoon were greatly diminished when Asian orography was removed (Hahn and Manabe, 1975; Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992). These numerical results were taken as confirmation of the importance of sensible heat fluxes from the broad, elevated plateau surface, and the idea that plateau heating drives the South Asian monsoon became sufficiently widespread to make its way into textbooks (e.g. Hartmann, 1994).

2) Modern theories of convectively coupled monsoon dynamics :

At the heart of the idea of Tibet as a dominant thermal forcing lies the realization that precipitation south of the plateau is the largest diabatic heat source, as mentioned above. In the classical view, this precipitation is assumed to be caused by moisture convergence induced by plateau sensible heating. This is essentially a moisture-convergence closure for monsoon convection, similar to moisture-convergence closures for convection that were used in early theories of tropical cyclones (e.g. Charney and Eliassen, 1964; Kuo, 1965) . The assumed positive feedback between large-scale moisture convergence and latent heating has been termed Conditional Instability of the Second Kind (CISK). These ideas for the workings of moist convection in monsoons persist to this day, with CISK explicitly argued to be the mechanism by which elevated surface heat fluxes from orography produce a strong South Asian monsoon (e.g. Wu et al., 2007; Chen et al., 2014). However, moisture-convergence closures for convection are now rarely used in theories and numerical models of other tropical circulations (e.g. Arakawa, 2004). In a review of convectively coupled circulations, Emanuel et al. (1994) went so far as to call CISK "an influential and lengthy dead-end road in atmospheric science." Theories of convective quasi-equilibrium (CQE) have taken its place. These theories posit that cumulus convection is a fast process that prevents large accumulations of convective available potential energy (CAPE), so that moist convection does not act as a heating that forces large-scale flow but instead maintains the vertical temperature structure of the troposphere near that of a moist adiabat. If convection does prevent large variations in CAPE, then tropospheric temperatures will covary with hb, the moist static energy of air below the base of cumulus clouds[2].

In short,

$$\boldsymbol{\delta h_b \propto \delta T_u} \quad (1)$$

where the b subscript denotes a property of air below cloud base, and u a property of the "upper" troposphere (i.e. the convecting layer above cloud base). The variations in hb and Tu represented in (1) can occur in time or in space, as long as moist convection exists to couple the subcloud layer with the free troposphere.

Monsoon dynamics in a CQE framework were first explored in highly idealized models, and although almost none of these contained orography they nevertheless laid the foundation for new thinking about Tibet. Using a model of intermediate complexity with a CQE parameterization for convection, Chou et al. (2001) showed that advection of low-hb air from extra tropical oceans into monsoon regions could suppress monsoon precipitation on the west side of continents and limit the pole ward extend of monsoons. This "ventilation" of warm and moist monsoon air by cold and dry extra tropical air was shown to operate in the North American, South American, and Asian monsoons (e.g. Chou and Neelin, 2001, 2003; Neelin, 2007). However, the model used to demonstrate this did not have orography, so its relevance to Asia remained questionable. In a general circulation model (GCM) with idealized boundary conditions, Privé and Plumb (2007b) showed that thin vertical walls on the east and west coasts of a rectangular, off-equatorial continent could suppress ventilation, strengthening monsoon precipitation and allowing it to extend further pole ward. They speculated that plateau orography could "have a very significant impact on the moist static energy distribution, by shielding India and Southeast Asia from inflow from the Asian mid latitudes."

Even though this CQE literature laid the foundation for a new view of orography as an insulator that inhibits ventilation, the idea that Tibet acts as an elevated heat source persisted. This is not surprising, because even if one abandons the idea that sensible heat fluxes from the plateau drive the monsoon via CISK, free-tropospheric temperatures and hb are known to equilibrate at values that increase with the elevation of the under- lying surface. Molnar and Emanuel (1999) demonstrated this in idealized simulations of radiative-convective equilibrium over surfaces of different heights, so it would seem reasonable to assume that this effect of surface elevation could constitute a large forcing not represented in the idealized CQE studies discussed above. Furthermore, no estimates of the distribution of subcloud hb over South Asia and Tibet were published until Boos and Emanuel (2009) conducted an observationally based analysis of South Asian monsoon onset in a CQE framework, and the upper-tropospheric temperature maximum was commonly assumed to lie directly over the Tibetan Plateau (e.g. see discussion in Privé and Plumb, 2007b).

3) Reevaluating the role of Tibet:

A year before Privé and Plumb speculated that Tibet might inhibit the penetration of cold mid latitude air into the South Asian monsoon, Chakraborty et al. (2006) showed that Asian orography in a GCM with realistic boundary conditions did inhibit this ventilation. But there was a twist: Chakraborty et al. (2006) found that Indian monsoon onset was delayed more by removal of orography in southwestern Asia (including the western third of the Tibetan Plateau) than by removal of orography in southeastern Asia (including the remainder of the plateau). They showed via estimates of meridional temperature advection in their GCM that the orography "acts as a barrier for the cold winds from the upper- latitudes". Although Chakraborty et al. (2006) did not refer to the previous literature on CQE monsoon dynamics, their work is essentially an application of the ventilation hypothesis of Chou and Neelin (2001) to the orography of Asia[3]. A clearer assessment of the relativeimportance of plateau heating and orographic insulation was provided by Boos and Kuang (2010).

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[1] Since monsoons and tropical cyclones can both be represented as idealized, warm-core axisymmetric vortices (e.g. Wirth and Dunkerton, 2006; Boos and Emanuel, 2008), one could imagine Tibet's sensible heat fluxes producing the warm core in the "eye" of the monsoon vortex, which in turn causes radial (i.e. meridional) moisture convergence, precipitation, and amplified ascent in the "eyewall" just south of the plateau.

[2] The moist static energy h = cpT + Lvq + gz, with cp the specific heat of air at constant pressure, Lv the latent heat of vaporization, g the gravitational acceleration, and T, q, and z representing temperature, specific humidity, and height, respectively. The equivalent potential temperature Θe is sometimes used in place of h; the two have similar distributions and are for the present purpose interchangeable.

Using reanalysis, radiosonde, and satellite data, they showed that peak hb during boreal summer lies over the non-elevated Indo-Gangetic plain south of the Himalayas, and peak upper-tropospheric temperatures lie over this hb maximum, as expected in a CQE state. These features are reproduced in the most recent reanalysis of the European Centre for Medium Range Weather Forecasts (ERA-Interim, Dee et al., 2011), as shown in Figure 1. Furthermore, large horizontal gradients in hb are coincident with orography, as one would expect if orography acts primarily as an insulator rather than a heat source. Horizontal gradients of hb are weaker over Tibet than over the Hindu Kush range west of Tibet, suggesting that surface elevation may indeed enhance hb but that this effect is not strong enough to make Tibet the thermal maximum. Boos and Kuang (2010) also conducted climate model integrations in which the plateau was flattened while the comparatively thin orography south and west of the plateau was preserved. With only that thin orographic barrier, the model produced a monsoon of nearly the same strength and horizontal structure as with a full plateau. Monsoon strength was similarly perturbed little by setting the surface albedo of the plateau to unity, which eliminates the ability of the plateau to serve as a heat source. Removing the plateau or setting its albedo to unity did reduce precipitation along the Himalayas, but this is a highly local response distinct from the large reduction in cross-equatorial monsoon flow that occurred when all orography was removed.

Although the hypothesis that orography acts primarily as an insulator has met with some objections, proponents of the "elevated heating" idea no longer claim that the horizontally extensive Tibetan Plateau is the dominant heat source. Instead, Wu et al. (2007) argued that sensible heat fluxes from the plateau's sloping boundaries (e.g. the Himalayas) constitute the dominant forcing for the South Asian monsoon, with these heat fluxes amplified through a CISK-like feedback. Wu et al. (2012) showed that the South Asian monsoon weakened in a climate model when surface sensible heat fluxes were eliminated from all Asian orography, and that precipitation along the Himalayas greatly diminished when sensible heat fluxes from the Himalayas were eliminated. Consistent with the shift away from the idea that elevated plateau heating drives the entire South Asian monsoon, Wu et al. (2012) concluded that a "striking feature of the present experiments is the insensitivity of the southern part of the SASM [South Asian Summer Monsoon] to IPTP [Iranian Plateau and Tibetan Plateau] forcing". So any argument in the literature is between proponents of the idea that the northern "branch" of the South Asian monsoon is driven by surface heat fluxes from mountain slopes amplified by a CISK-like feedback (e.g. Wu et al., 2012) and proponents of the idea that the entire South Asian monsoon is greatly amplified by the suppression of ventilation by orography (e.g. Chakraborty et al., 2006; Boos and Kuang, 2010). There may actually be little disagreement since Boos and Kuang (2010) did find that plateau heating enhanced precipitation along the Himalayas; they simply classified this as a relatively minor and local response to plateau heating distinct from the non local response of the interhemispheric, large-scale South Asian monsoon to orographic insulation.

Any monsoon, even in regions without orography, is fundamentally caused by horizontal gradients in the energy supplied to the atmosphere by external sources such as radiation and surface heat fluxes (e.g. Neelin and Held, 1987). Suppressing land surface heat fluxes in the summer hemisphere of a climate model is thus expected to reduce monsoon strength whether or not the land surface is elevated, and the central question is whether the monsoon is more sensitive to heat fluxes from elevated or non-elevated surfaces. Boos and Kuang (2013) showed that South Asian monsoon strength in a climate model was more sensitive to surface heat fluxes emitted by non-elevated parts of northern India than to heat fluxes from Himalayan slopes. They argued that this is expected, because the maxima in hb and upper-tropospheric temperature lie over the non-elevated parts of northern India, and a thermally direct circulation will respond most strongly to heating in coincident with its thermal maximum.

Other findings support the idea that Tibet's thermal forcing is not especially important for the monsoon. Years of strong South Asian precipitation are accompanied by an enhanced land-sea contrast in hb, with the largest hb increase lying over the Indo-Gangetic plain and little signal seen over Tibet (Hurley and Boos, 2013). Rajagopalan and Molnar (2013) found that h_b over Tibet does covary with Indian rainfall, but only during the very early and late parts of the monsoon; they estimated that at most 20% of total summer rainfall might be explained by plateau heating. Finally, Boos and Hurley (2012) showed that the latest ensemble of global climate models has a negative bias in h_b over northern India that seems to be associated with the orographic smoothing that is inevitable at the resolutions of those models

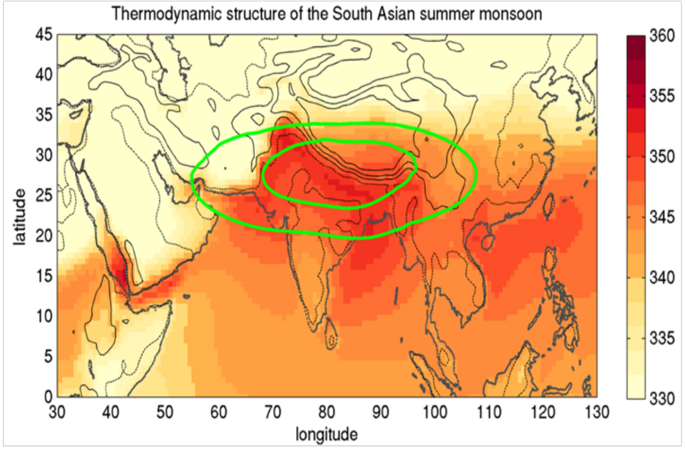

Figure 1: ERA-Interim June-August climatological mean (1979-2012) thermodynamic structure of the South Asian monsoon. Shading shows moist static energy about 40 hPa above the surface, represented in K by dividing by the specific heat of dry air at constant pressure. Green contours show temperature averaged 200-400 hPa (the 245.5 and 246.5 K isotherms). Dotted black line is the 300 m topographic contour and solid black lines are topographic contours starting at 1.5 km with a 1.5 km interval

This under representation of peak topographic heights seemed particularly important in the Hindu Kush just west of Tibet, consistent with Chakraborty et al. (2006) and with the importance of the orographic insulation mechanism (the lowest hb in South Asia lies just west of the Hindu Kush, e.g. Fig. 1).

4) An updated view of "ventilation" :

A more comprehensive examination orography's role was conducted by Ma et al. (2014), who applied surface height and surface heat flux perturbations to a global model having substantially finer resolution — 40 km in the horizontal — than used in any of the studies discussed above. Ma et al. (2014) confirmed that removal of the Tibetan Plateau had little effect on South Asian monsoon strength provided the Himalayas and adjacent mountain ranges were preserved. They confirmed that monsoon strength was most sensitive to heat fluxes from non-elevated surfaces just south of the Himalayas in the location of the hb maximum, with heat fluxes from Himalayan slopes being less important for monsoon strength. But their most novel finding was that the proportionality constant implicit in the CQE relation

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3 It should be noted that Chakraborty et al. (2006) also argued for an absolute threshold in hb over India, rather than the critical horizontal gradient of hb shown to be relevant by Emanuel (1995)

(1) was larger when orography was flattened than when surface heat fluxes were eliminated. This seemed to occur because removing orography allowed dry extra tropical air to intrude into the monsoonal free-troposphere where it was entrained into convective updrafts and increased the hb needed to maintain a given amount of CAPE. This is an important modification of the CQE frameworks that have been applied to monsoon dynamics (e.g. Emanuel, 1995; Chou and Neelin, 2001; Privé and Plumb, 2007a; Boos and Emanuel, 2009). This modification, which merits further examination and quantification, is consistent with previous work that shows moist convection is sensitive to free-tropospheric humidity in ways that cannot be captured by the form of CQE that assumes CAPE is a function only of hb and free-tropospheric temperature (e.g. Derby shire et al., 2004; Holloway and Neelin, 2009).

More generally, the concept of monsoon "ventilation" needs to be updated to emphasize the deleterious effect of dry desert air on monsoon strength. The original idea of ventilation posited that cold and dry air from extra tropical oceans could inhibit the strength and pole ward extent of monsoons (e.g. Chou and Neelin, 2001; Neelin, 2007; Privé and Plumb, 2007b; Boos and Kuang, 2010). However, the region with lowest hb adjacent to the monsoon thermal maximum is the desert region of western Pakistan, Afghanistan, and Iran. Thus, orography prevents the hot and dry air of continental deserts from penetrating the monsoon thermal maximum, rather than the cold and dry air of extra tropical oceans. This grants the greatest importance to orography west of Tibet (e.g. the Hindu Kush), consistent with the perturbed orography model experiments of Chakraborty et al. (2006) and Boos and Hurley (2012), although the former did not seem to recognize the importance of dry desert air intrusions. Perhaps if the Hindu Kush and Iranian Plateau ever attained elevations higher than those at present, this may have produced an especially intense South Asian monsoon.

5) Concluding remarks:

Since the 1950s, the horizontally extensive surface of the Tibetan Plateau was thought to drive the South Asian summer monsoon. Although several competing hypotheses have been published in the past decade to explain the influence of orography on this monsoon, all agree that the monsoon instead owes its great strength to the comparatively narrow Himalayas, Hindu Kush, and adjacent mountain ranges. There is widespread agreement that Tibet is not the primary thermal forcing, as evidenced by numerical climate models (Chakraborty et al., 2006; Boos and Kuang, 2010; Wu et al., 2012; Ma et al., 2014), the observed thermodynamic structure of the mean summer monsoon (Boos and Emanuel, 2009; Boos and Kuang, 2010), and the spatial structure of interannual variations in monsoon rainfall and subcloud hb (Hurley and Boos, 2013; Rajagopalan and Molnar, 2013).

Orography greatly strengthens the interhemispheric South Asian monsoon circulation by preventing ventilation of the convective maximum by dry extra tropical air. This conclusion is the fairly natural extension of a series of studies on CQE monsoon dynamics (Chou and Neelin, 2001, 2003; Privé and Plumb, 2007b; Boos and Emanuel, 2009). Heat fluxes from the elevated slopes of the Himalayas contribute to local precipitation along those mountains, but this is a local effect limited to the northernmost part of the South Asian monsoon (Boos and Kuang, 2010; Wu et al., 2012). Theoretical progress on convectively coupled tropical dynamics shows that a misplaced emphasis on surface sensible heat fluxes formed the cornerstone of the "elevated plateau heating" idea and its requisite CISK feedback. Both sensible and latent heat fluxes are equally important to monsoon strength in a CQE framework, and the thermally direct monsoon circulation must export the energy that is fluxed into the atmospheric column by the sum of these surface enthalpy fluxes and the convergence of radiative fluxes.

Open questions on the role of orography in monsoons still abound. For example, can simple theoretical models of CQE monsoon dynamics be modified to incorporate the effects of free-tropospheric moisture? Since temperatures do increase with the elevation of the underlying surface in the theoretical state of radiative-convective equilibrium (e.g. Molnar and Emanuel, 1999), why doesn't the thermal state of the Tibetan Plateau play a stronger role in the South Asian monsoon? What role is played by the north-south oriented mountains on the west coasts of southern India and Myanmar (e.g. do they simply organize precipitation or do they actually enhance the domain-mean monsoon precipitation)? How does elevated topography alter the gross moist stability (e.g. Neelin and Held, 1987) of the South Asian monsoon? Modern theories of convectively coupled circulations are only beginning to be applied to domains with orography, so the coming decade could be a time of great progress in understanding the South Asian monsoon.

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Land-atmosphere interactions in monsoon regimes and future prospects for enhancing prediction

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Introduction

Monsoons are annual large-scale phenomena that form an integral part of global-scale circulations. Monsoon circulations are driven and maintained by seasonal contrasts in the thermal heating of land and sea. Beginning in spring, the land warms. Sensible and latent heat are released from the land surface into the atmosphere, driving the formation of low pressure that induces air flow from the ocean. The heating in the land triggers convection, producing clouds and generating rain. The monsoon flow is intensified by convective uplift as well as topographic forcing where mountains exist. These forcing and thermal gradients influence the strength, duration, and spatial distribution of large-scale monsoon systems (e.g., Dirmeyer, 1998; Webster et al., 1998; Xue et al., 2004). Therefore, land/atmosphere interaction plays a crucial role in monsoon systems by their very nature.

Monsoons exhibit substantial seasonal, interannual, and decadal variability that results in severe droughts, such as the most significant West African drought in the last century (e.g., Xue et al., 2010a), and floods such as those occurred recently in central China (Ding et al., 2008). Land surface processes may play an important role in these extreme events through modulating the heat gradient and moisture supply (e.g., Xue and Shukla, 1993; Xue, 1996). Despite the importance of the monsoonal systems in providing water for agriculture in many of the world's most populous regions, the effect of land/atmosphere interactions in the monsoon system is still poorly understood. Figure 1 shows the sources of moisture supplying rainfall over the major monsoon systems of the world (Dirmeyer et al. 2014), estimated using a water vapor back-trajectory analysis algorithm (cf. Dirmeyer and Brubaker 2007). The classical monsoon circulation features are evident, bringing oceanic moisture inland, but within those circulations a great deal of the rainfall comes from moisture recycled over land from terrestrial evaporation. These land surface fluxes provide a means for land-atmosphere interactions to modulate the monsoons, as further described below.

Identification of the role of land in the monsoon system

It has been shown that land surface processes have considerable influence over the monsoon regions. The Global Land–Atmosphere Coupling Experiment (GLACE: Koster et al., 2004; 2006; Guo et al. 2006) investigated soil moisture/atmosphere coupling strength across the globe during boreal summer with multiple general circulation models (GCMs). Figure 2a shows estimates averaged across twelve of the participating models, with higher values implying a higher control on precipitation anomalies by the soil moisture conditions. This multi-model estimation of land atmosphere coupling strength reveals that monsoon regions, such as the Sahel and South Asia,have some of the strongest soil moisture/climate couplings in the world. This has been borne out in regional modeling studies over specific monsoon regions (e.g., Steiner et al. 2009; Saha et al. 2011; 2012).

The mechanism identified in GLACE favors strong land-atmosphere interactions in transition regions between arid and humid regimes (Dirmeyer et al. 2009). In dry locations with abundant radiative energy there is a strong control on surface fluxes by soil moisture; its availability increases latent heat flux and its absence results in net radiation going into sensible heat flux. However, in arid regions the dry atmosphere is unresponsive to small additions of moisture. On the other hand, in warm humid regions the atmosphere is often near moist convective instability, and the addition of additional moisture to the atmospheric profile can decrease stability, increase clouds and convection. However, fluxes at the land surface, especially when modulated by vegetation as discussed below, are insensitive to variations in soil moisture unless the soil becomes very dry. Only in the regions between arid and humid does one find a degree of sensitivity in both the land surface and atmosphere, so that the feedback loop is complete.

In addition to soil moisture, the land surface has other avenues of interaction with the atmosphere. These processes include radiative transfer in the canopy and the associated radiation balance at the surface, transpiration by vegetation due to stomatal control and its connection to root water uptake,canopy interception loss, and variations in aerodynamic resistances of momentum and heat due to vegetation morphology and land use practices. We refer to this collection as biogeophysical processes (BGP). The impact of BGP on the climate system has been investigated using the GCMs coupled to different benchmark land parameterizations with varying degrees of physically-based complexity in their representation of BGP (Xue et al., 2004b, 2006, 2010b): one land model has fully interactive BGP/atmosphere interaction (but no dynamic vegetation);another consists of only two-way direct soil moisture interaction with the atmosphere but no vegetation, and a third has specified soil moisture and other land attributes, such albedo and roughness length. The importance of BGP effects on climate were assessed based on the skill of simulations of observed variables by GCMs with different land benchmark models. The statistically significant reduction of errors between simulated variables and the observation was adopted as the criteria to identify BGP effects. Observational and reanalysis data were used for the applications of these criteria. Figure 2b shows the reduced absolute mean bias of 5-year summer precipitation simulations (or improved prediction skill) with this approach due to inclusion of BGP process in the GCM (Xue et al., 2010b). Figures 2a and 2b, from two entirely different approaches, show consistency in identifying the West African and South Asian monsoon regions as hot-spots of land/atmosphere interaction. Meanwhile, the second approach has identified more regions including some in the Southern Hemisphere because Figure 2a only includes boreal summer effects. Figure 2c shows regional average BGP/atmosphere coupling strength in different seasons (Xue et al., 2010b)

BGP has the greatest impact on monsoon regions during the local summer and the local fall.

The controls of the land surface on the atmosphere described above are all in terms of positive feedbacks though the water cycle. There are also regimes of negative water cycle feedbacks that are relevant to monsoons, particularly on the dry margins of monsoon systems like the Sahel, the southwestern United States, Northwest India and Pakistan (Ferguson and Wood, 2011; Ferguson et al. 2012; Taylor et al. 2012). In such locations a dry soil advantage for cloud formation and convection can exist where deeper boundary layers driven by extra sensible heating are more advantageous than additional moistening by latent heat flux (Findell and Eltahir 2003).

Land use and land cover change (LULCC) and monsoons

The impact of LULCC has been extensively investigated in land/monsoon interaction studies, which along with the soil moisture studies are among the two most investigated subjects in land/atmosphere interaction research.

The South American monsoon system is unique in that its main source of moisture is largely terrestrial rather than oceanic, coming from over the rainforests of the Amazon (Fig 1). The Amazon Basin contains the largest extent of tropical forest on Earth and the rapid expanse of agriculture and timber harvest since the 1950s has led to large-scale deforestation (Nobre et al., 2004).Many studies with GCMs and regional climate models (RCMs) have investigated the impact of tropical deforestation on the regional and global climate (e.g., Dickinson and Henderson-Sellers 1988; Nobre et al. 1991; Polcher and Laval 1994; Sud et al., 1996; Xue et al., 1996; Samapioet al., 2007; Correia et al., 2008). Almost all models produce higher surface temperature and lower evaporation over the deforested areas. Field experiments such as the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) have been conducted to support such research (Nobre et al., 2004). However, these studies disagree on the impact of deforestation on precipitation, as most modeling studies have indicated patterns of both decreasing and increasing rainfall along with shifting seasonal changes. Since the South American monsoon was first identified (Zhou and Law, 1998) studies have explored BGP process effects on the South American monsoon development (e.g., Xue et al., 2006), but no studies have specifically focused on the LULCC impact on this monsoon system.

LULCC in the West African monsoon system has been the subject of much investigation. Since Charney's first study (1975) on albedo and North African drought, this subject has been surrounded by controversy over the role of land degradation, its extent and consequences on Sahelian drought. For instance, satellite evidence (Nicholson et al., 1998) shows that albedo change in West Africa has been less than that required by the radiatively-driven hypothesis for drought in the Charney et al. (1997) study. Their proposed cooling with higher surface albedo was inconsistent with the general warming associated with surface roughness changes accompanying land degradation (Ripley, 1996). Furthermore, it has been found that in the Northern Hemisphere descent regions of the Hadley circulation, the time-mean horizontal advection term was twice as strong as the time-mean diabatic-cooling term that the albedo effect would produce (Rodwell and Hoskins, 1996).

Therefore, more realistic BGP-based land-surface models are needed to assess realistically the impact of desertification on the Sahel drought. A proper evaluation of the surface feedback to climate can be obtained only when all comparable components of the energy and water balances are considered. In the coupled GCM/BGP model, it was found that after a dramatic vegetation reduction, land degradation could lead to regional monsoon climate changes of the order of the differences found between the 1980s (a severe drought period) and the 1950s (a very wet period), with warming and reductions in the summer monsoon rainfall, runoff, and soil moisture over the Sahel region. The impact is not limited to the specified desertification areas but it also south of this area due to modifications in the circulation (Xue and Shukla, 1993; Xue, 1997; Xue et al., 2004).

Furthermore, despite the consensus that the sea surface temperature (SST) may play a major role in the West African drought, the Climate of the 20th Century international project (C20C; Kinter and Folland 2011) with multiple state-of-the-art GCMs forced by observed SSTs found most models failed to produce observed droughts while two models simulated only half the magnitude of the Sahel monsoon rainfall changes between the 1980s and the 1950s. Scaife et al. (2008) conclude that the Sahel drought is only partly forced by SST anomalies. To achieve a better understanding of the external forcing on the West African monsoon decadal variability, the West African Monsoon Modeling Experiment (WAMME) has been designed to use multiple GCMs and RCMs to elucidate the relative roles of SST, LULCC, and aerosols in West African monsoon variability (Xue et al., 2010a; Boone et al., 2010).

The effect of LULC changes on South Asian and East Asian monsoons and global climate have also been studied (e.g., Dirmeyer and Shukla, 1996; Xue, 1996;Fu et al., 2003; Takataet al., , 2009; Li and Xue, 2010; Niyogi et al., 2010; Mahmood et al., 2004). A companion to agriculture in semi-arid regions is increased irrigation, and several studies have suggested the recent expansion of irrigation in Northwest India and Pakistan could be having deleterious effects on monsoon precipitation (Douglas et al. 2009; Saeed et al. 2009; Tuinenberg et al. 2012; Guimberteau et al. 2012; Wei et al. 2013). With more LULCC data available from different sources showing substantial LULCC in past decades (e.g., Hurtt et al., 2006; Kim et al., 2014) and experience gained from the previous multi-model studies (e.g., Pitman et al., 2009), LULCC effects in the monsoon system can be more realistically assessed.

Future Perspectives

The relationship between changes in the slowly varying boundary conditions at the earth's surface (e.g., SST and BGP) and changes in atmospheric circulation and rainfall are the focus of much research. More comprehensive investigation is required;realistic simulation of monsoons and better understanding of its processes remain a formidable task. In the recent CLIVAR land-monsoon initiative, several key issues were identified for further investigation: land/atmosphere feedbacks (vegetation, dust), short time-scale tie-ins with intra-seasonal variability work, longer timescale efforts to understand the impact of different model land use treatments and inter-model differences, and identifying where and when hot spots of land-atmosphere coupling occur. Multi-model experiments with carefully selected and benchmarked land parameterization and adequate diagnostic metrics (with the associated data required) are necessary to diagnose monsoon land-surface interactions more completely.

Dynamic vegetation models have been developed for two-way land/monsoon interaction studies, such as the West African Sahelian drought study (Zeng et al., 1999; Wang and Eltahir, 1999). Although such models are still at the preliminary stage, several studies with the West African monsoon as a prime subject have demonstrated their promising potential.

The study by Zeng et al.(1999) illustrated how the combination of multiple feedbacks, each with its own time constant,recreates realistic rainfall variability. Especially when a drought is persistent, the ecosystems themselves may migrate. However, recent CMIP5 results have revealed that these models exhibit significant deficiencies in decadal climate simulations (Murray-Tortarlo et al., 2013). Proper model evaluations with observational data are necessary to employ dynamic vegetation models for the land/monsoon interaction studies.

GLACE-2 (Koster et al. 2010; 2011) demonstrated that improved prediction skill can be achieved by realistic land surface initialization. However, realistic land initialization is not sufficient if the model climate is unrealistic, i.e., if there exists strong climate drift in the model. The role of model biases in the atmosphere as well as lands a limit to our predictive capability needs to be evaluated. The quality of land surface initialization also depends on the quality of forcing data for land surface analyses, particularly precipitation (Oki et al. 1999; Koster et al. 2011), but operational monitoring of precipitation is lacking in many monsoon areas and needs to be improved. Monitoring of surface fluxes, boundary layer development and soil moisture in monsoon regions would also help advance process-level understanding of land-atmosphere interactions in these regimes. These efforts would put us in a better position to advance monsoon research, particularly for the purposes of prediction.

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Figures :

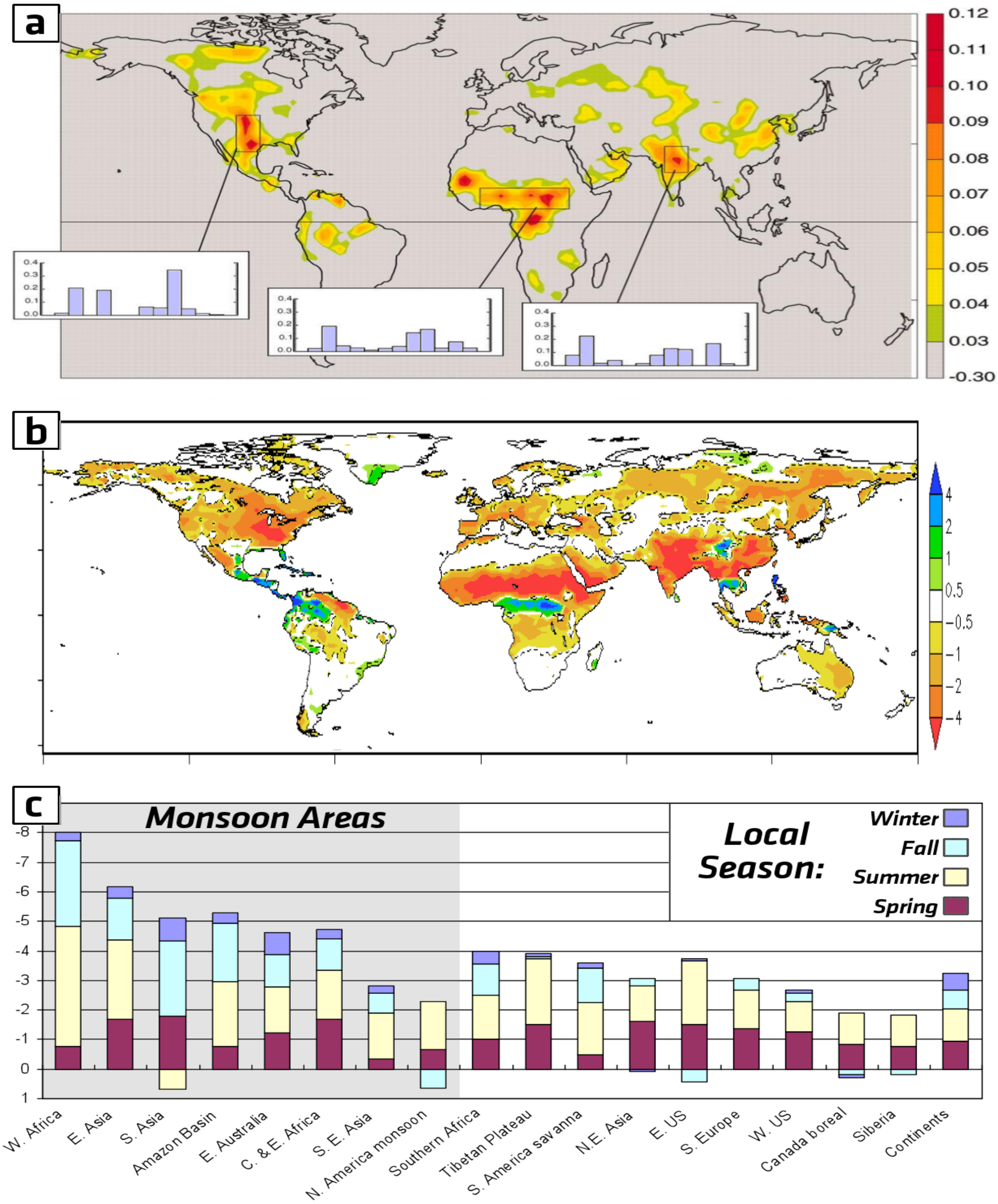

Figure 1: a) Hot spots of land-atmosphere coupling from the multi-model GLACE experiment (dimensionless; reproduced from Koster et al. 2004); b) change in local summer precipitation bias (mm d-1) due to inclusion of land surface BGP processes in a single climate model (Xue et al., 2010b); c) average BGP/atmosphere coupling strength in different seasons (mm d-1) from Xue et al. (2010b)with monsoon regions highlighted.

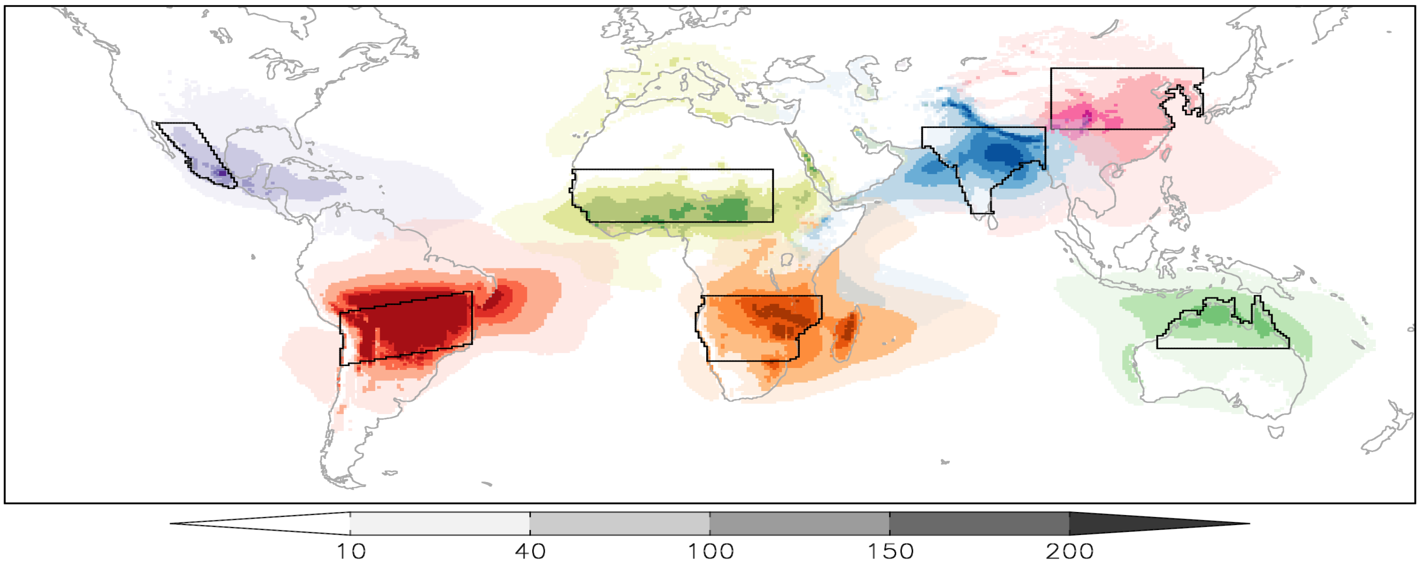

Figure 2: Evaporative source (kg m-2) supplying rainfall over the outlined monsoon regions during July-August in the Northern Hemisphere, January-February for Southern Hemisphere, derived from the quasi-isentropic back trajectory data set of Dirmeyer et al., (2014) for 1979-2006. Levels of shading for each color follow the grey scale at the bottom

Recent advances in monsoon intraseasonal prediction

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Introduction

The monsoon intraseasonal oscillation (MISO), also known as boreal summer ISO (BSISO), is one of the most prominent sources of short-term climate variability in the Asian summer monsoon (ASM) and global monsoon system (Webster et al., 1998; Wang and Ding, 2008) with two distinctive periodicities: 30-60 days (e.g., Wang et al., 2005) and 10-20 days (e.g., Kiguchi and Wang, 2010). It affects summer monsoon onsets (Wang and Xie, 1997; Kang et al., 1999), the active/break phase of the monsoon (Annamalai and Slingo, 2001; Goswami, 2005; Ding and Wang, 2009), the monsoon seasonal mean (Krishnamurthy and Shukla, 2007)and extra tropical atmospheric circulation (Ding and Wang, 2005; Moon et al., 2013). Due to the oscillating nature of the MISO, it has been recognized that it may be potentially predictable several weeks in advance depending on approaches and variables. van den Dool and Saha (1990) estimated a lead-time of two months as an upper limit of its predictability. By using an observation-based method, Ding et al. (2011) assessed predictability of the MISO-related daily outgoing long-wave radiation (OLR) to be about 35 days. Approaches with ensemble simulations of a single dynamical model suggested that MISO-related circulation might have longer predictability (about 30-40 days) than convective variables (approximately 15-30 days) (Waliser et al., 2003; Liess et al., 2005; Reichler and Roads, 2005). Under a multi-model framework, Lee et al. (2014b) estimated the BSISO is potentially predictable up to 45 days.

During recent decades, MISO prediction using coupled models has been advanced owing to improvement in model physics and initialization (Vitart and Molteni, 2009; Fu et al.,2009, 2011; Waliser et al., 2011). However, the current status of MISO forecast skill is still limited due to model deficiencies regarding accurate representation of initiation, structure, intensity, and propagation of the MISO and errors in initial and boundary conditions (Waliser, 2006, 2011; Seo et al., 2007; Fu et al., 2011, 2013). Several international collaborations have been coordinated to advance the MISO/BSISOprediction. To facilitate monitoring and real-time forecast activities of the BSISO, two BSISO indices have been defined as a part of the Madden-Julian Oscillation (MJO) Task Force (MJO-TF) activity based on multi-variate empirical orthogonal function (MV-EOF) analysis of daily anomalies of OLR and 850-hPa zonal wind in the ASM region (Lee et al., 2013). BSISO1, composed of the first two principal components (PCs) of the MV-EOF, represents the canonical northward propagating variability that often occurs in conjunction with the eastward propagating MJO with quasi-oscillating periods of 30-60 days. BSISO2, defined by the third and fourths PCs, mainly captures the northward/northwestward propagating variability with periods of 10-30 days during primarily the pre-monsoon and monsoon-onset season.

Motivated by significant societal demands for reliable Subseasonal prediction, the coordinated Intraseasonal Variability Hind cast Experiment (ISVHE) was launched in 2009 (Mani et al., 2014; Lee et al., 2014a,b).The coupled models participating in the project show a useful anomaly correlation coefficient skill of 0.5 for the BSISO indices up to 15 to 25 days for the 20 years of 1989-2008 (Lee et al., 2014b). Since the 2013 boreal summer, real-time forecast activities of the BSISO indices have been operated at the APEC Climate Center (APCC) in cooperation with the Working Group on Numerical Experimentation (WGNE) and MJO-TF. Currently five operational models are participating in the forecasts (Wheeler et al., 2014).Validation for the 2013 summer case indicates that the operational models have a useful skill for the BSISO indices up to at least 20 days. In particular, the European Centre for Medium Range Weather model has a higher skill than other models and its correlation skill of the BSISO1 reaches 0.7 at 20-day forecast lead.

The Subseasonal-to-Seasonal (S2S) prediction project under the World Weather Research Programme and World Climate Research Programme has two plans to advance MISO prediction in the coming 5 years. The first project is to produce forecasts and develop metrics targeting MISO at multi-week lead times. The second focuses is on case studies of the monsoon onset. The former aims to develop a set of societally and scientifically relevant ISO forecast metrics that are applicable to all of the major monsoon systems and assess multi-week forecast skill based on hind cast evaluation in addition to MISO predictability across all key monsoon systems. The latter aims to evaluate multi-week forecast skill to predict the onset for each monsoon under a multi-model framework and assess representation of the monsoon onset in forecast models so as to guide forecast model development.

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Long-term anthropogenic drivers of monsoons

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Introduction

Monsoons are the most important mode of seasonal climate variation in the tropics, and are responsible for a large fraction of the annual rainfall in many regions. Their strength and timing is related to atmospheric moisture content, land-sea thermal contrast, land cover and use, atmospheric aerosol loadings, and other factors.

Time evolution of global mean forcing from 1750 to the present is shown in Figure 2. During this period, greenhouse gases (GHG) are the dominant term over long periods, while the volcanic eruption is the dominant term at very short periods. GHG warming acts to increase monsoon rainfall due to the increased water vapor in the atmosphere (Kitoh et al., 2013). The stronger cooling over the middle-to-high latitudes of East Asia than that over the tropical ocean associated with the eruption of big volcanoes can lead to a reduced land–sea thermal contrast and favors a weaker East Asian summer monsoon (EASM) circulation (Man et al., 2014). Any land use changes alter the reflectivity (albedo) of the land surface, and thus the intensity of solar radiation absorbed, potentially with additional changes in surface moisture. Atmospheric aerosol may influence climate directly through scattering and absorbing radiation, thus perturbing how much solar radiation reaches the ground. Absorption of solar radiation by aerosol, on the other hand, also warms the atmosphere, changing the atmospheric heating distribution. Aerosols may also influence the climate indirectly by acting as cloud condensation nuclei or ice nuclei, modifying the optical properties and lifetime of clouds. In addition, strong volcanic eruptions irregularly occur and have a strong negative radiative forcing. Changes of total solar irradiance since 1750 are smaller than any other forcing. Therefore, monsoons have been and will continue to be affected and modulated by variations of natural and anthropogenic drivers on various time scales.

Greenhouse Gases

The strongest effect of climate change upon the modern-era monsoons is the increase in atmospheric moisture associated with warming of the atmosphere, which is brought about by GHG increase, resulting in an increase in total monsoon rainfall. . The atmospheric concentration of carbon dioxide has increased by 40% since preindustrial times, and is projected to increase further under all Representative Concentration Pathways (RCP) scenarios used in the Intergovernmental Panel on Climate Change (IPCC)Fifth Assessment Report, ranging up to more than three times the preindustrial level (IPCC, 2013). Atmospheric moisture content is enhanced by GHG warming, which leads to a more intense water cycle throughout the atmosphere. Climate model projections through the 21st century show an increase in total monsoon rainfall, largely due to increasing atmospheric moisture content. Extreme precipitation events over monsoon regions will become more intense and more frequent. How much moisture is available depends on warming and, therefore, choosing future scenario is critical to project monsoon precipitation changes in the future.

Aerosols

Loading of atmospheric aerosols varies from region to region, affecting regional climate. The direct effect of aerosol acts to reflect solar radiation reaching the ground, resulting in cooler surface temperatures. Land-sea thermal contrast becomes smaller than in the absence of the aerosol direct effect, and the summer monsoon circulation becomes weaker. Model simulations of the Asian monsoon show that the sulphate aerosols' direct effect reduces the magnitude of precipitation change compared with the case of only GHG increases (Bollasina et al., 2011; Polson et al., 2014; Song et al., 2014). The Coupled Model Intercomparison Project (CMIP5) includes various forcing experiments, including "Historical" simulations using all forcing, "HistoricalNat" using natural forcing only, and "HistoricalGHG" simulations using GHG forcing only. Using these data sets, one can investigate different effects of forcing on the global monsoon precipitation changes in the historical period. Neither the simulations with GHG-forcing only nor natural-forcing only reproduce the decreasing trend of global monsoon precipitation during the 20th century simulated by the all-forcing simulation, suggesting that the aerosol forcing is essential for reproducing monsoon precipitation changes. Attribution studies show that anthropogenic aerosol has been the dominant influence on Northern Hemisphere monsoon precipitation over the second half of the 20th century (Polson et al., 2014). Regionally, changes in circulation and precipitation contradict each other. The combination of various kinds of aerosol in the historical climate simulation of CMIP5 models led to a weakened EASM circulation, while the increase of GHG resulted in an enhanced EASM circulation (Song et al., 2014).

Aerosol species with high absorptivity such as black carbon absorb solar radiation in the lower atmosphere, cooling the surface, stabilizing the atmosphere, and reducing precipitation (Ramanathan et al., 2001). However the total effect of black carbon is not well known because it induces complicated cloud responses. The emissions of anthropogenic aerosols will ultimately decrease in response to air quality policies, which would suppress their negative influence on monsoon rainfall in the long-term future.

Land-use change

Land cover/use changes affect the energy and water balance at the Earth's surface through changes in surface albedo, evapotranspiration and roughness. Deforestation and afforestation both have impacts on GHG concentration. Reconstructions on land use at 1750, 1900 and 1992 are shown in Figure 1. Land use changes occurred even before 1750 widely over Asia and Europe due to agricultural development. In India and China, between 1700 and 1850, forest area has decreased from 40-50% coverage to 5-10% by conversion to cropland. These extended land-use changes are believed to have resulted in a decrease in monsoon rainfall over the Indian subcontinent and southeastern China (Takata et al., 2009). Land-use change from forest to cropland causes the surface roughness to decrease, resulting in increased surface wind speed and a reduction of moisture convergence and precipitation. The reduction in precipitation reduces the soil moisture and, hence, local evaporation and moist convection, creating a positive feedback of further precipitation reductions.

However, reconstructions of past land cover changes are limited (Gaillard et al., 2010), and thus more detailed work is needed to understand the effects of land cover on past monsoon activity.

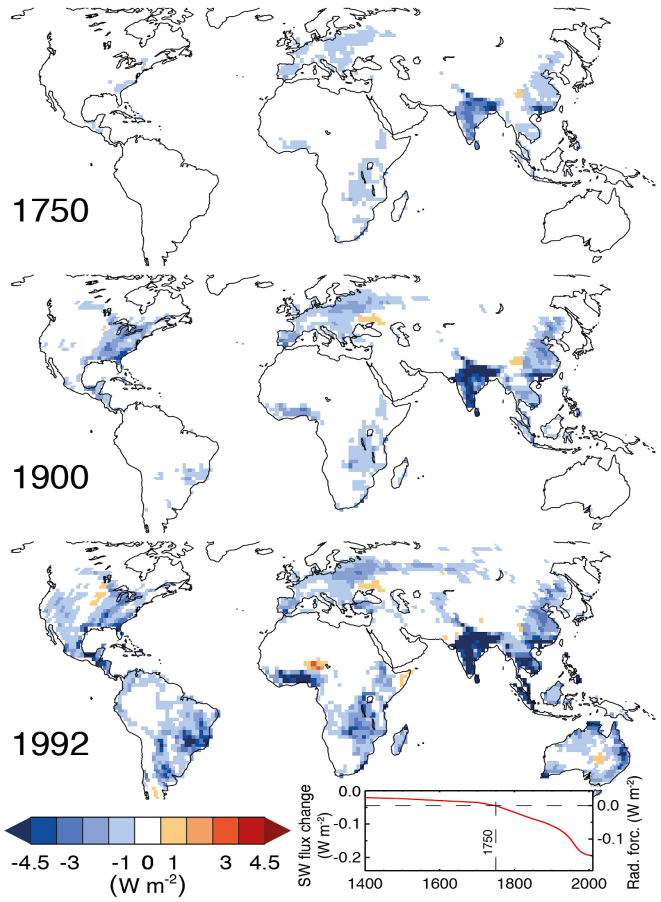

Figure 1 : Reconstructions on land use at 1750, 1900 and 1992

Recommendations for CMIP6

Decadal-scale variations in monsoons have been observed in the past. Understanding how well state-of-the-art climate models can reproduce the observed changes in regional monsoons is a precondition for evaluating the reliability of future climate change projections made by these models. The relative contributions of internal variability such as the Pacific Decadal Oscillation/Inter-decadal Pacific Oscillation (PDO/IPO)and external forcing in driving the historical evolution of monsoons and other modes of variability in the Earth System should be addressed in CMIP6. One approach is a continuation of the above-mentioned historical experiments in which various external forcing are switched on/off. In order to improve such an approach, relevant forcing data including aerosol emissions and land use/cover must be prepared and evaluated with sufficient spatial and temporal resolution. The increasing evidence demonstrating that some parts of the decadal variability in global and regional monsoons are driven by PDO/IPO-related sea surface temperature (SST) anomalies (Li et al., 2010; Zhou et al., 2008, 2013) also suggests a need for appropriate experiments to explore this in CMIP6. We suggest "pace-maker" experiments in which the tropical lobe of PDO/IPO-related SST is restored to observational values using nudging techniques, but elsewhere in the globe the ocean-atmosphere coupling is maintained. To this end, we invite participation in the coordinated monsoon modeling experiments of CMIP6.

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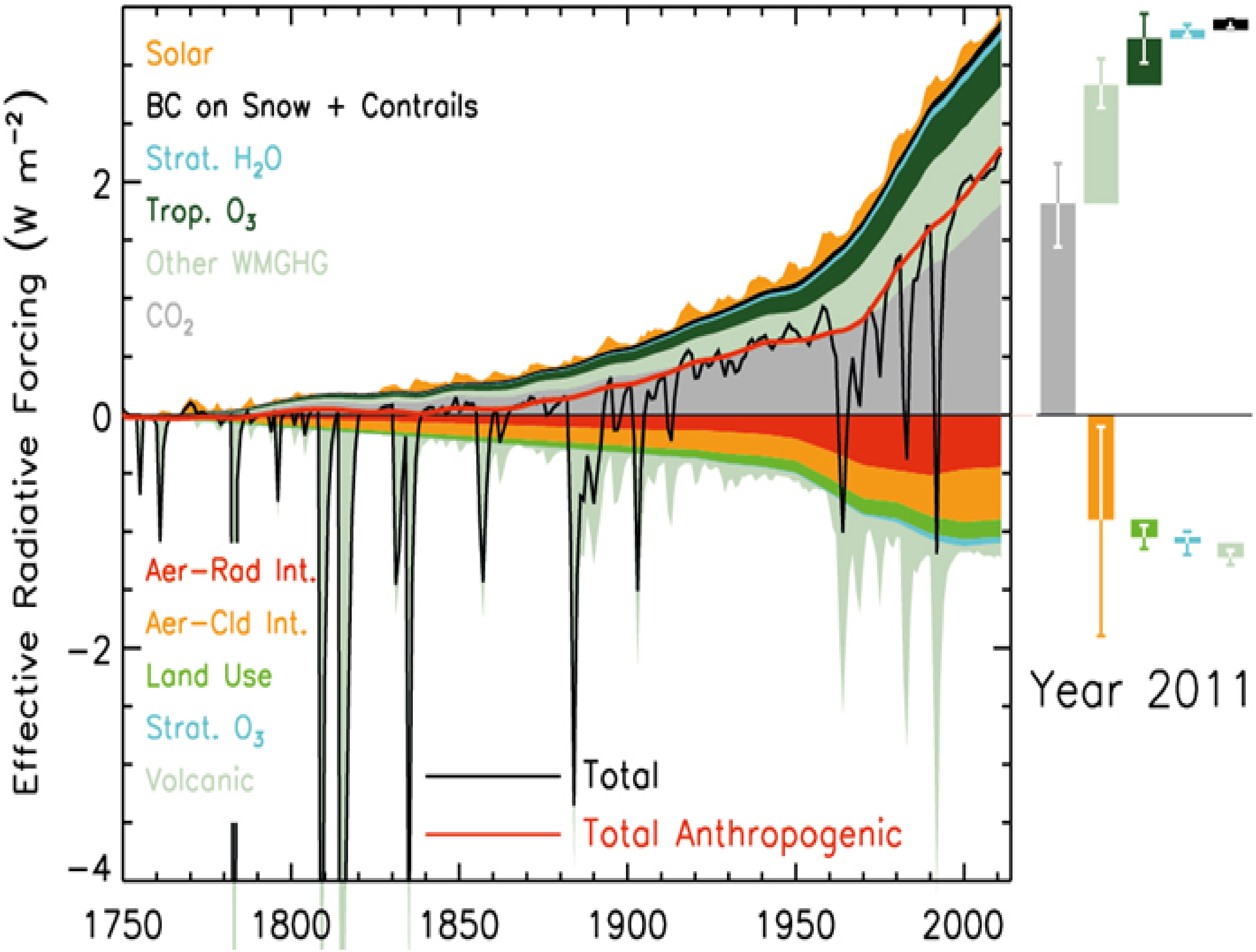

Figure 2 : Time evolution of anthropogenic and natural forcing mechanisms. Bars with the forcing and uncertainty ranges (5 to 95% confidence range) at present are given in the right part of the figure. For aerosol the effective radiative forcing (ERF) due to aerosol radiation interaction and total aerosol ERF are shown. The uncertainty ranges are for present (2011 versus 1750). For aerosols, only the uncertainty in the total aerosol ERF is given. For several of the forcing agents the relative uncertainty may be larger for certain time periods compared to present. The total anthropogenic forcing was 0.57 (0.29 to 0.85) W m−2in 1950, 1.25 (0.64 to 1.86) W m−2in 1980 and 2.29 (1.13 to 3.33) W m−2in 2011. Taken from Figure 8.18 of IPCC WGI AR5 (2013).

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