Scientific Report (August 2007 – July 2014)

Title: Future Projections of Mean and Variability of the Asian Summer Monsoon and Indian Ocean Climate Systems

Project ID 0013709
Prog. Mgr: Renu Joseph
PI H. Annamalai
Award Register # ER64445

Highlights

1. Training of post-docs (younger generation) in climate science
2. Nature Climate Change – review article
3. Invited Book chapters – 3
4. Invited presentations in major international conferences –
5. Total publications (acknowledged the project) – 16

Scientific accomplishments

1. Objective assessment of coupled models' representation of monsoon and Indian Ocean variability patterns
2. Elucidated moist and radiative processes in initiating and maintaining monsoon extended breaks
3. Identified role of dry air advection in initiating dryness over monsoon region during developing El Nino
4. Demonstrating how SST rise over tropical western Pacific caused long term declining trend in observed monsoon rainfall during the last six decades
5. In a warmer planet, the role of SST rise over the tropical Indian Ocean in maintaining the monsoon annual cycle
6. A comprehensive and succinct review article in Nature Climate Change on monsoons
7. Process-oriented (moist static energy budget analysis) diagnostics for monsoon research

Models used for sensitivity studies in the research

1. GFDL Atmospheric General Circulation Model (AM2.1)
2. IPRC regional climate model
3. Linear baroclinic model developed by Dr. Watanabe

Diagnosis of CMIP3/5 model integrations (preindustrial, historical and future scenarios)

1. Diagnosis of mean monsoon, intraseasonal variability and ENSO-monsoon association
2. Analysis of annual cycle of various regional monsoons
3. Monsoon-Eastern Mediterranean dynamical linkage

Summary

The overall goal of this project is to assess the ability of the CMIP3/5 models to simulate the Indian-Ocean monsoon systems. The PI along with post-docs investigated research issues ranging from synoptic systems to long-term trends over the Asian monsoon region. The PI applied diagnostic tools such as moist static energy (MSE) to isolate: the moist and radiative processes responsible for extended monsoon breaks over South Asia, precursors in the ENSO-monsoon association, reasons for the drying tendency over South Asia and the possible effect on tropical Indian Ocean climate anomalies influencing certain aspects of ENSO characteristics. By diagnosing various observations and coupled model simulations, we developed working hypothesis and tested them by carrying out sensitivity experiments with both linear and nonlinear models. Possible physical and dynamical reasons for model sensitivities were deduced.

On the teleconnection front, the ability of CMIP5 models in representing the monsoon-desert mechanism was examined recently. Further more, we have applied a suite of diagnostics and have performed an in depth analysis on CMIP5 integrations to isolate the possible reasons for the ENSO-monsoon linkage or lack thereof. The PI has collaborated with Dr. K.R. Sperber of PCMDI and other CLIVAR Asian-Australian monsoon panel members in understanding the ability of CMIP3/5 models in capturing monsoon and its spectrum of variability.

The objective and process-based diagnostics aided in selecting models that best represent the present-day monsoon and its variability that are then employed for future projections. Two major highlights were an invitation to write a review on present understanding monsoons in a changing climate in Nature Climate Change, and identification of an east-west shift in observed monsoon rainfall (more rainfall over tropical western Pacific and drying tendency over South Asia) in the last six decades and attributing that shift to SST rise over the tropical western Pacific.

On the training of post-doctoral scientists: the PI spent considerable amount of time and efforts in introducing the post-docs into climate modeling and designing the numerical experiments. With training provided and knowledge gained, post-docs worked in the project obtained long term positions elsewhere. The PI also enjoyed the experience in managing the works and educating work ethics to the younger generation.

Based on the research achievements and publications, the PI gave invited talks in major international monsoon conferences/workshops, and gave lectures in various research organizations in the last six years. Finally, during the project period, the PI attended all the DOE organized PIs meeting and presented the major results.

Some of the major implications of the project include: (i) Sustained observational efforts are necessary to monitor the three-dimensional moisture distribution over the Asian monsoon region that would aid in better understanding, modeling and predicting severe monsoons well in advance and (ii) process-based diagnostics lead pathways for model improvements.

Detailed Report

1. Post-doc hiring and mentoring

Early in August 2007, we announced the post-doc vacancy in the CLIVAR Asian-Australian Monsoon Panel email list maintained by Prof. Carlos Ereno, the job announcement email list maintained by the Japan Meteorological Agency, and also to all the major research institutions in India. Out of the 15 prospective applications for the post, 3 were short-listed and reference letters were sought. The PI interviewed all the 3 short-listed candidates over phone. Based on the qualifications, job requirements and the interview, the job was offered to Dr. Hae-Kyung Drbohlav. She graduated with distinction from the Meteorology Department of the University of Hawaii in 2002, and then had post-doc experiences at INGV, Italy for two years and also at COLA, MD for 18 months. Her expertise on monsoon modeling and diagnostics of coupled model outputs to understand Indian Ocean Climate systems very well matched the job requirements. Since joined the IPRC in January 2008.

In the fall of 2007, the PI approached the program manager to convert the 4-year fund allocated to the graduate student to hire a 3-year post-doc due to declining of the offer by a student and then non-availability of students at that time. Ms Bamzai readily agreed to the request and the search for this post-doc was taken up. Dr. Prasanna obtained his Ph. D from Nagoya University, Japan under the supervision of Prof. Yasunari. Based on his advisor's recommendation, and telephone interview, Dr. Prasanna was hired and joined IPRC in May 2009. His expertise on monsoon processes, in particular land-atmosphere interactions was thought to be instrumental in understanding the projected extended monsoon breaks and persistence of droughts over the monsoon domain.

Due to personal reasons, Dr. Drbohlav quit her post-doc position on December 31, 2008. After extensive search, Dr. Prasanth Pillai, a recent Ph. D graduate from Cochin University, India was offered the job. Dr. Pillai has done extensive diagnostic work, mostly with observations and reanalysis products on monsoon interannual variability. He joined the project in June 2009.

Since June 2009, the PI and the post-docs met as a group once a week, and discussed the details of the problems at hand, and the various approaches to address them. Both the post-docs were introduced to climate modeling, and the PI and Dr. Hafner, a Senior Programmer at the IPRC helped them in implementing the models in DOE machines and designing the numerical experiments. The weekly group meeting immensely helped in exchange of ideas and "helping and learning from each other attitudes". The PI spent considerable amount of time and energy in infusing the ideas to the post docs and in writing scientific manuscripts.

During early 2012, both the post docs obtained long-term scientist positions (India and Korea) and left the IPRC. Since then, the PI had hard time in finding a replacement and had to request for no-cost extensions to wind up the works by himself.

2. Model implementation in DOE machines

In early 2009, Dr. Jan Hafner, scientific programmer at the IPRC who is partly supported by the grant, made test runs with the GFDL AGCM in the local computers. Initially, he faced some compiler errors but with help from the GFDL atmospheric modeling group, he was able to fix them. Then, during the summer/fall of 2009, he implemented the AGCM in the DOE computing systems (Bassi and Franklin). After carrying out some test runs, we performed idealized runs to test hypotheses. We submitted a proposal to INCITE that was not awarded.

In late 2009 and early 2010, Hafner implemented IPRC_RegCM and SCOAR coupled model in the DOE computing systems (Hopper). We (post-docs and Jan) have performed a series of 20-year runs with IPRC_RegCM in an ensemble mode to test various hypotheses. Then, we are performed some idealized experiments with SCOAR to understand the importance of aerosol forcing on the regional monsoon circulation and rainfall. Later, we had to discard SCOAR simulations because of large systematic errors in monsoon precipitation climatology.

During every stages of model implementation and sensitivity experiments, DOE computing staff offered timely and invaluable assistance to our team. We sincerely appreciate that.

During 2013, we implemented CCSM4 coupled model.

In summary, DOE computers were extensively used to perform a suite of model simulations to test our working hypotheses – the timely help of the DOE computing staff is greatly appreciated - without that support it would have been impossible to achieve our goals.

3. Scientific accomplishments

The scientific works performed during the project are classified into five categories and they are: (i) Future projections of mean monsoon and synoptic systems; (ii) interannual variability; (iii) intraseasonal variability; (iv) CMIP3/5 diagnostics and (v) monsoons in a changing climate. A brief summary of scientific accomplishments in each category is now presented. Details are available in the referred publications.

(i) Future projections of mean Monsoon and synoptic systems (Stowasser et al. 2009)

We examine future projections of mean monsoon and synoptic systems in the GFDL_CM_2.1 model simulations in which quadrupling of CO_2 concentrations are imposed. In a warmer climate, despite a weakened cross-equatorial flow, the time-mean precipitation over peninsular parts of the India increases by about 10-15%. This paradox is interpreted as follows: The spatially well-organized anomalous precipitation over the eastern equatorial Indian Ocean forces twin anticyclones as a Rossby-wave response. The southern component of the anticyclone opposes and weakens the climatological cross-equatorial monsoon flow, thereby limiting coastal upwelling along Somalia. As a result, the sea surface warms along the Somalian coast and evaporation becomes a local maximum over the southern Arabian Sea. That is, in addition to the increased CO_2-induced rise in temperature, evaporation, and atmospheric moisture, the local air-sea interaction, further increases SST, evaporation, and atmospheric moisture leading to increased rainfall over peninsular parts of India. The IPRC Regional Climate Model (RegCM) that has a nearly three times higher horizontal resolution than the GFDL model was integrated for 20 years, with lateral boundary conditions taken from the GFDL model. The hypothesis that in a warmer climate, increase in troposphere moisture favor more intense monsoon depressions is tested. The GFDL model does not reveal changes, but the RegCM suggests a statistically significant increase in the number of storms that have wind speeds of 15-20 ms^{-1}.

(ii) Monsoon Interannual variability: how tropical SST anomalies impact monsoon precipitation?

(a) Moist dynamical linkage between the equatorial Indian Ocean and the south Asian monsoon trough (Annamalai, 2010, J. Atmos. Sci).

The mechanism through which the SST anomalies over the eastern equatorial Indian Ocean modulate the monsoon trough is investigated through a series of sensitivity experiments with a linear baroclinic model. The forcing, the SST patterns, is derived from a composite analysis performed on the 20th century runs of the GFDl_CM_2.1 model. The solutions unequivocally demonstrate that advection of moisture by the divergent winds is the primary source for the enhancement of the monsoon trough during years of cold SST anomalies over the equatorial Indian Ocean. Additionally, the equatorial Indian Ocean and the monsoon trough are connected by a thermally direct local meridional circulation.

(b) Moist dynamics of severe monsoons: role of tropical SST (Pillai and Annamalai, 2012, J. Atmos. Sci.)

Diagnostics from both observations and multi-century integrations of the Geophysical Fluid Dynamics Laboratory (GFDL) coupled model (CM2.1) indicate that about 80% of the severe monsoons (>1.5 standard deviations in rainfall to its long term mean) over south Asia are associated with sea surface temperature (SST) anomalies over the equatorial Pacific during the developing phase of El Niño – Southern Oscillation (ENSO). The primary focus here is to identify the moist processes through which dryness (wetness) is initiated over south Asia in spring and maintained through summer during El Niño (La Nina). Our hypothesis, based on composites constructed from CM2.1 simulations, is that at low-levels El Niño forced equatorial easterly wind anomalies over the Indian Ocean, due to Ekman pumping, promotes anticyclonic vorticity over the northern Indian Ocean. The poleward flank of this anticyclone advects dry air from northern latitudes to south Asia. The hypothesis is tested through performing ensemble simulations with AM2.1. During El Niño, contribution by dry advection dominates the negative rainfall anomalies over south Asia from April onwards. The anticyclonic vorticity over the northern Indian Ocean forms 20-25 days earlier than the organization of negative rainfall anomalies over south Asia. During ENSO, the long lead-time embodied in this precursor signal can be exploited for predicting severe monsoons over south Asia. The major results are summarized in the schematic shown below (Fig. 1).

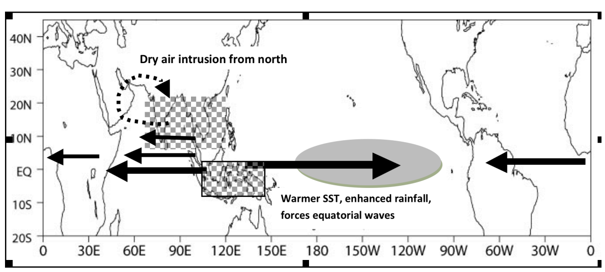

Figure 1: Schematic illustrating possible mechanism through which El Nino impacts monsoon.

(iii) Boreal summer intraseasonal variability

(a) Coupled model simulations of boreal summer intraseasonal variability, Part I: Systematic errors and caution on use of metrics. (Sperber and Annamalai, 2008, Clim. Dyn., 2008):

Boreal summer intraseasonal (30-50 day) variability (BSISV) over the Asian monsoon region is more complex than its boreal winter counterpart since it exhibits northward and northwestward propagating convective components near India and over the west Pacific. Here we analyze the BSISV in the CMIP3 and two CMIP2+ coupled ocean-atmosphere models. Though most models exhibit eastward propagation of convective anomalies over the Indian Ocean, difficulty remains in simulating the life cycle of the BSISV, as few represent its eastward extension into the western/central Pacific. As such, few models produce statistically significant anomalies that comprise the northwest to southwest tilted convection, which results from the forced Rossby waves that are excited by the near-equatorial convective anomalies.

(b) Poleward propagation of boreal summer intraseasonal oscillations in a coupled model: Role of Internal Processes (Ajayamohan, Annamalai et al. 2011, Clim. Dyn.,):

The study compares the simulated poleward migration characteristics of boreal summer intraseasonal oscillations (BSISO) in a suite of coupled ocean-atmospheric model sensitivity integrations. The sensitivity experiments are designed in such a manner to allow full coupling in specific ocean basins but forced by temporally varying monthly climatological sea surface temperature (SST) adopted from the fully coupled model control runs. In the presence of realistic easterly vertical shear, the continuous emanation of Rossby waves from the equatorial convection is trapped over the monsoon region that enables the poleward propagation of BSISO anomalies in all the model sensitivity experiments. To explore the internal processes that maintain the tropospheric moisture anomalies ahead of BSISO precipitation anomalies, moisture and moist static energy budgets are performed. In all model experiments, advection of anomalous moisture by climatological winds anchors the moisture anomalies that in turn promote the northward migration of BSISO precipitation.

(c) Moist dynamics of extended monsoon breaks over South Asia (Prasanna and Annamalai 2012, J.Climate)

An examination of observed daily rainfall over central India shows that short breaks (breaks lasting for 3 days) and extended breaks (breaks persisting for 7 days or more) are more frequent. A similar analysis with all the 5 members of CM2.1 runs for the period 1961-2000 shows that the model also captures the frequent occurrences of short and extended breaks. An examination of space-time evolution of rainfall and other associated variables suggest that before the establishment of extended breaks, active convection prevails over the tropical west Pacific, and during the break enhanced convection is noted over the equatorial Indian Ocean.

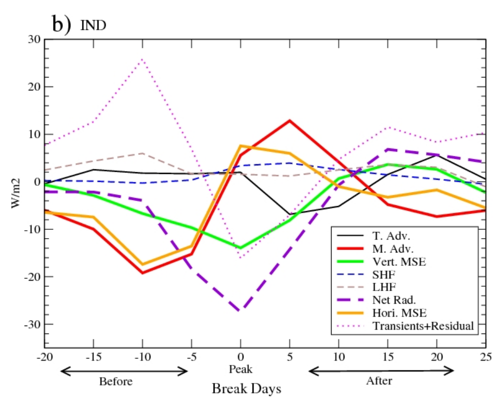

Figure 2: Leading terms of the moist static energy equation averaged over central India. Day 0 refers to time of maximum dryness over India. This figure illustrates that horizontal advection of dry air initiates breaks while cloud-radiation maintains them.

A suite model experiments has been performed to address the hypothesis that the extended break is initiated by descending Rossby waves (advection of dry air from north) forced by tropical west Pacific convection while it is maintained by cloud-radiation feedbacks and import of dry air due to local Hadley circulation forced by equatorial Indian Ocean convection. **Figure 2** provides the leading terms of the moist static energy budget averaged over central India. It is clear that 10-15 days before the initiation of breaks dry air advection dominates the budget while a reduction in MSE illustrative of downward motion together with radiative cooling maintains the extended breaks.

(iv) Monsoons in a changing climate

(a) Global warming shifts monsoon circulation, drying south Asia (Annamalai et al. 2013, J. Cli):

A simple running mean applied on the observed all-India rainfall (AIR) index depicts multi-decadal variability or epochs with a recurrent period of about 30-40 years. Based on its recurrent nature, the expected positive epoch during 1990s did not occur. Is this drying tendency (reduction in monsoon rainfall) due to human-induced anthropogenic forcing? Most remarkably, in CM2.1 20^{th} century integrations, all the 5-members capture the current drying pattern over south Asia, and increasing rainfall over tropical west Pacific. We test the hypothesis that western Pacific rainfall increase forces descent anomalies over south Asia through Rossby waves. We performed a 5 member 50-year experiments by forcing the GFDL_AM2.1 by observed month-wise incremental SST trend for the period 1951-2000. The forcing regions include: (i) tropical west Pacific; (ii) Indo-Pacific warm pool, and (iii) global tropics. The precipitation response to SST warming over tropical Indo-Pacific warm pool captures the drying pattern over south Asia and increase in rainfall over tropical west Pacific. While moisture convergence and precipitation dominate the moisture budget, the contributions from moisture advection and evaporation are substantial over south Asia, and tropical west Pacific. In summary, AM2.1 sensitivity experiments support our hypothesis. (**FIG. 3**)

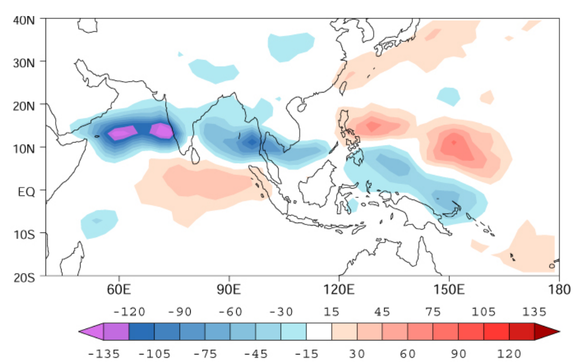

Figure 3: AGCM precipitation response during boreal summer to global SST trend during 1951-2005 – this result based on 25 member ensemble. This figure illustrates the observed east-west shift in monsoon rainfall is possibly due to SST rise over tropical western Pacific.

(b) Climate change and the South Asian monsoon (Turner, A., and H. Annamalai, 2012: Nature Climate Change)

The vagaries of South Asian summer monsoon rainfall on short and long timescales impact the lives of more than one billion people. Understanding how the monsoon will change in the face of global warming is a challenge for climate science, not least because our state-of-the-art general circulation models still have difficulty simulating the regional distribution of monsoon rainfall. However, we are beginning to understand more about processes driving the monsoon, its seasonal cycle and modes of variability. This gives us the hope that we can build better models and ultimately reduce the uncertainty in our projections of future monsoon rainfall. (**Fig. 4**)

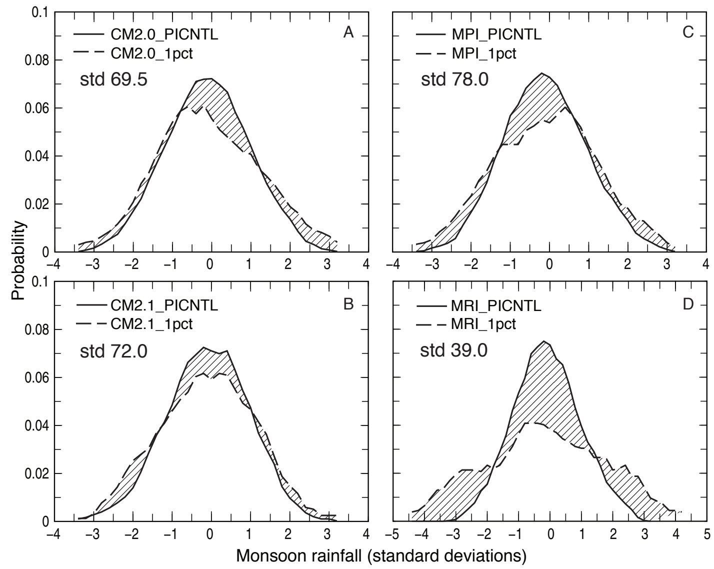

Figure 4: Probability density functions of interannual variability in monsoon rainfall in control and future climate scenarios. Shown are normalized probabilities of occurrences in four CMIP3 models. Preindustrial control (solid) and 1% per year increase in CO_2 concentrations (dashed) are shown. The future variations are scaled by preindustrial control interannual standard deviations. The differences in the shape of the PDFs have been tested for significance based on K-S test (after Turner and Annamalai 2012).

(c) Modeling the Monsoons in a Changing Climate – (H. Annamalai, 2011 – A Book Chapter in: E. Carayannis (Ed.), *Planet Earth 2011 - Global Warming Challenges and Opportunities for Policy and Practice*, InTech)

Over half of the World's population resides in regions influenced by the Asian Summer Monsoon (ASM). The seasonal mean (June through September) rainfall associated with the ASM is the primary source of water for the agrarian society. To a great extent, the livelihood and socio-economic issues of the people are influenced by the vagaries of the monsoon rainfall. Given their anticipated population rise, the countries experiencing the monsoon will likely face increased stress in issues such as drinking water supply, among other factors. It is therefore important to know how the ASM and its variability would respond in a warmer climate.

(d) Detection and attribution of Climate Change. (H. Annamalai, 2014 – A Book Chapter in *Climate Change and Water Resources* - S. Shrestha , M.S. Babel, and V.P. Pandey (Eds.),., CRC Press, Print ISBN: 978-1-4665-9466-1, eBook ISBN: 978-1

This chapter is intended for non-specialists in climate science and provides basic and elementary background on our current understanding of climate change, in par- ticular the phrase *global warming* that has attracted the public attention in recent years. We begin by outlining the basic physics involved in conjunction with the competing influences of greenhouse gases (GHGs) and aerosols on the climate system. Undoubtedly, future state of the climate system can only be obtained by running climate models in supercomputers. A challenge for climate modeling community is to demonstrate credibility for the model-simulated future climate scenario. This can only be accomplished if the model simulations also detect a climate change signal as observed for the current climate. Further, confidence in climate model-projected future changes is enhanced only if we understand the interactive processes that make up the future climate system. Such a systematic approach boosts the reliability of the projected changes and any impact assessment studies then provides pathways for making meaningful policy changes.

(e) Monsoon variability in a changing climate (Annamalai and Sperber, 2014 – A Book Chapter in "Global Monsoons" Eds. L. M. V. Carvalho and C. Jones, Springer International Publishing.Charles Jones (in press)

This chapter provides a succinct review on the current understanding of the South Asian summer monsoon and the ability of present-day climate models to represent its variability in a changing climate. Beginning with a processes-based review of the large and regional scale aspects of the monsoon precipitation climatology, the systematic model errors in precipitation and monsoonal diabatic heating are also highlighted. In climate models, certain necessary conditions for representation of synoptic systems, boreal summer intraseasonal variability, and the ENSO-monsoon teleconnection are presented. This is followed by discussion of the improved (or lack thereof) performance of climate models in simulating natural modes of variability. Lastly, we evaluate the ability of models to simulate the observed long-term declining trend in the seasonal mean monsoon rainfall, including possible mechanisms for this trend. Despite dedicated efforts, there is a lack of substantial improvement in monsoon modeling, which 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 an observational effort, improving the physical processes in numerical models will be severely limited.*

(v) Monsoon and its variability in CMIP3/5 model integrations

(a) Monsoon Regimes and Processes in CCSM4. Part I: The Asian–Australian Monsoon (Meehl et al. 2012, J. Climate)

The simulation characteristics of the Asian–Australian monsoon are documented for the Community Climate System Model, version 4 (CCSM4). Comparisons are made to an Atmospheric Model Intercomparison Project (AMIP) simulation of the atmospheric component in CCSM4 [Community Atmosphere Model, version 4, (CAM4)] to deduce differences in the monsoon simulations run with observed sea surface temperatures (SSTs) and with ocean–atmosphere coupling. In general, monsoon rainfall is too heavy in the uncoupled AMIP run with CAM4, and monsoon rainfall amounts are generally better simulated with ocean coupling in CCSM4. There is a reduction of the systematic error of rainfall over the tropical Indian Ocean for the South Asian monsoon, and well-simulated connections between SSTs in the Bay of Bengal and regional South Asian monsoon precipitation. The pattern of rainfall in the Australian monsoon is closer to observations in part because of contributions from the improvements of the Indonesian Throughflow and diapycnal diffusion in CCSM4. Intraseasonal variability of the Asian–Australian monsoon is much improved in CCSM4 compared to CCSM3 both in terms of eastward and northward propagation characteristics, though it is still somewhat weaker than observed. An improved simulation of El Niño in CCSM4 contributes to more realistic connections between the Asian–Australian monsoon and El Niño–Southern Oscillation (ENSO), though there is considerable decadal and century time scale variability of the strength of the monsoon–ENSO connection.

(b) The Asian Summer Monsoon: An Intercomparison of CMIP5 vs. CMIP3 Simulations of the Late 20th Century (Sperber, Annamalai et al. 2013, Clim. Dyn)

The boreal summer Asian monsoon has been evaluated in 25 Coupled Model Intercomparison Project-5 (CMIP5) and 22 CMIP3 GCM simulations of the late twentieth Century. Diagnostics and skill metrics have been calculated to assess the time-mean, climatological annual cycle, interannual variability, and intraseasonal variability. Progress has been made in modeling these aspects of the monsoon, though there is no single model that best represents all of these aspects of the monsoon. The CMIP5 multi-model mean (MMM) is more skillful than the CMIP3 MMM for all diagnostics in terms of the skill of simulating pattern correlations with respect to observations. The onset of the monsoon over India is typically too late in the models. The anti-correlation between anomalies of all-India rainfall and Niño3.4 sea surface temperature is overly strong in CMIP3 and typically too weak in CMIP5. For both the ENSO-monsoon teleconnection and the East Asian zonal wind-rainfall teleconnection, the MMM interannual rainfall anomalies are weak compared to observations. Though simulation of intraseasonal variability remains problematic, several models show improved skill at representing the northward propagation of convection and the development of the tilted band of convection that extends from India to the equatorial west Pacific.

(c) South Asian summer monsoon and the eastern Mediterranean climate: the monsoon-desert mechanism in CMIP5 simulations (Cherchi, Annamalai et al. 2014, J. Climate).

Dry summers over the eastern Mediterranean are characterized by strong descent anchored by long Rossby waves, which are forced by diabatic heating associated with summer monsoon rainfall over South Asia. The large-scale teleconnection between rising and subsiding air masses is referred to as the "monsoon–desert mechanism." This study evaluates the ability of the phase 5 of the Coupled Model Intercomparison Project (CMIP5) models in representing the physical processes involved in this mechanism. An evaluation of statistics between summer climatologies of monsoon diabatic heating and that of vertical velocity over the eastern Mediterranean suggests a linear relationship. Despite large spatial diversity in monsoon heating, descent over the Mediterranean is coherently located and realistic in intensity. To measure the sensitivity of descent to the diversity in the horizontal and vertical distribution of monsoon heating, a series of linear atmosphere model experiments are performed. It is shown that column-integrated heating over both the Bay of Bengal and the Arabian Sea provides the largest descent with a more realistic spatial pattern. In the vertical, CMIP5 models underestimate the diabatic heating at upper levels, while they overestimate it at lower levels, resulting in a weaker forced response and weaker associated descent over the Mediterranean. A moist static energy budget analysis applied to CMIP5 suggests that most models capture the dominant role of horizontal temperature advection and radiative fluxes in balancing descent over the Mediterranean. Based on the objective analysis herein, a subset of models is identified that captures the teleconnection for reasons consistent with observations. The recognized processes vary at interannual time scales as well, with imprints of severe weak/strong monsoons noticeable over the Mediterranean.

(d) The use of fractional accumulated precipitation for the evaluationof the annual cycle of monsoons. (Sperber and Annamalai 2014, Clim. Dyn, in press)

Using pentad rainfall data we demonstrate the benefits of using accumulated rainfall and fractional accumulated rainfall for the evaluation of the annual cycle of rainfall over various monsoon domains. Our approach circumvents issues related to using threshold-based analysis techniques for investigating the life-cycle of monsoon rainfall. In the Coupled Model

Intercomparison Project-5 models we find systematic errors in the phase of the annual cycle of rainfall. The models are delayed in the onset of summer rainfall over India, the Gulf of Guinea, and the South American Monsoon, with early onset prevalent for the Sahel and the North American Monsoon. This, in combination with the rapid fractional accumulation rate, impacts the ability of the models to simulate the fractional accumulation observed during summer. The rapid fractional accumulation rate and the time at which the accumulation begins are metrics that indicate how well the models concentrate the monsoon rainfall over the peak rainfall season, and the extent to which there is a phase error in the annual cycle. The lack of consistency in the phase error across all domains suggests that a ''global'' approach to the study of monsoons may not be sufficient to rectify the regional differences. Rather, regional process studies are necessary for diagnosing the underlying causes of the regionally-specific systematic model biases over the different monsoon domains. Despite the afore-mentioned biases, most models simulate well the interannual variability in the date of monsoon onset, the exceptions being models with the most pronounced dry biases. Two methods for estimating monsoon duration are presented, one of which includes nonlinear aspects of the fractional accumulation. The summer fractional accumulation of rainfall provides an objective way to estimate the extent of the monsoon domain, even in models with substantial dry biases for which monsoon is not defined using threshold-based techniques.

4 Major contributions to Monsoon and Indian Ocean research

1. Observed weakening tendency – apart from aerosols forcing, SST rise over tropical western Pacific plays an important role in the east-west shift in monsoon rainfall.
2. Future monsoon projections – despite persistence of systematic errors in the simulation of monsoon precipitation climatology, in a warmer climate, seasonal-mean monsoon rainfall shows a slight increase – this is attributed to SST rise and enhanced surface evaporation over the tropical Indian Ocean
3. ENSO-monsoon association – severe weak monsoons over south Asia are witnessed primarily during the developing phase of El Nino. Identification of the source of dry air advection and appreciable lead time noted provides a framework for predicting monsoon deficit during an developing El Nino
4. Extended monsoon breaks over south Asia – apart from identifying the role of dry air in initiating monsoon breaks, the importance of cloud-radiation feedbacks in maintaining the dryness is quantified.
5. Monsoon interannual variability changes in a warmer planet – even among the "best" models that capture the ENSO-monsoon association in both the current and future projected climates, large uncertainty exists in assessing the future projected severe weak and strong monsoons
6. Systematic errors in CMIP3/5 models – while there are improvements in certain individual models, the large-scale errors in monsoon precipitation climatology still persists suggesting little improvement – most models fail to represent the basic annual cycle associated with the Asian-Australian monsoon systems

5 Publications:

Annamalai, H., M. Mehari, and K. R. Sperber, 2014: A recipe for ENSO-monsoon diagnostics in CMIP5 models. J. Clim. (in preparation)

Annamalai, H. and K. R. Sperber, 2014: Asian monsoon variability in a changing climate. In "The Monsoons and Climate Change." Eds. L. M. V. Carvalho and C. Jones, Springer International Publishing. (in press)

Cherchi., A., H. Annamalai, S. Masina and A. Navarra., 2014: South Asian monsoon and eastern

Mediterranean climate: the monsoon-desert mechanism in CMIP5 models. *J. Climate* **27** (18), 6877-6903

Annamalai, H., 2014: Detection and attribution of Climate Change. In S. Shrestha , M.S. Babel, and V.P. Pandey (Eds.), *Climate Change and Water Resources.*, CRC Press, Print ISBN: 978-1-4665-9466-1, eBook ISBN: 978-1-.

Sperber, K. R., and H. Annamalai, 2014: The use of fractional accumulated precipitation for the evaluation of the annual cycle of monsoons. Clim. Dynam. DOI: 10.1007/s00382-014-2099-3 (in press)

Annamalai, H., J. Hafner, K.P. Sooraj and P. Pillai, 2013: Global warming shifts monsoon circulation, drying South Asia. *J. Climate*, **26** (9), 2701-2718

Sperber, K.R., H. Annamalai, I.-S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou, 2013: The Asian Summer Monsoon: An intercomparison of CMIP5 vs CMIP3 simulations of the late 20th Century. *Clim. Dyn.,* **41** (9-10), 2711-2744

Pillai, P., and H. Annamalai 2012: Moist dynamics of severe monsoons over South Asia: Role of the tropical SST. *J. Atmos. Sci.,* **69,** 97-115.

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6 Presentations in major international conferences and research organizations

During the project period, the PI delivered many invited lectures in major international monsoon workshops and conferences and advertised the project research results. Furthermore, talks were delivered in major research organizations. Post-docs also attended AMS and other conferences and presented their results. Jan Hafner attended intensive computing course conducted by DOE computing facilities.