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Modeling the Monsoons in a Changing Climate

H. Annamalai
IPRC/SOEST, University of Hawaii
USA

1. Introduction

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.

Climate change refers to various facets of climate, but the effect receiving the widest attention is referred to as global warming. Today, the principal concern is to understand the physical processes that determine the mean temperature of the Earth's surface, and interpret how this may change in response to changes in atmospheric composition. Since the temperature and atmospheric moisture content are inherently related the obvious question is how the global hydrological cycle will respond to changes in temperature. Observations over the last 1000 years indicate that carbon dioxide (CO_2) amount has increased by 25% since the industrial revolution, and continues to increase at a rate of 0.5 per annum. In other words, by releasing considerable amount of CO_2 into the atmosphere, humans have applied a stronger forcing with the potential for irreversible effects. To address and assess the impact of this additional forcing, scientists around the world turn to mathematical models of the Earth's climate system. These climate models are constructed based on the physical principles and executed on the most powerful computers. Various hypotheses are tested to understand the present climatic condition. A classic example is that the observed increase in global mean surface temperature since 1950s is reproducible *only* if the greenhouse gases are included in the model simulations (IPCC 2001). This surface warming is projected to increase into the 21st century (IPCC 2007). These models also suggest that under increased CO_2 forcing, global hydrological cycle will intensify (Held and Soden 2006). However, regional precipitation projections from these models have large uncertainties.

Recognizing the strengths and weaknesses of the models, appropriate tools are employed to interpret the future projections. This is the "need of the hour" as policy and decision-makers seek to mitigate and adapt to the undesirable impact of climate change caused by human intervention. Over half of the World's population lives in regions influenced by the Asian monsoon (Webster et al. 1998). The seasonal mean rainfall, both summer (June through September) and winter (October through December), associated with the monsoons

influence the people lives, particularly the small-scale farmers. For a variety of reasons, it is desirable to know whether the time-mean monsoon precipitation will increase or decrease as global temperature continues to warm, and understand how the increase in time-mean atmospheric water vapor would influence the severity of droughts and floods, and other monsoon characteristics such as extreme rainfall events, number of rainy days, and extended breaks.

The remaining of the chapter is organized as follows. In Section 2, our current understanding of the monsoon as a coupled ocean-atmosphere-land system is presented followed by the ability of the climate models in simulating its current mean monsoon precipitation and the future time-mean monsoon rainfall projections. In Section 3, monsoon variability is presented starting with the ENSO-monsoon association, the projected floods and droughts, monsoon onset and subseasonal variations and finally their future projections. In Section 4, the uncertainties in model projections and policy matters are mentioned. In Section 5, the way forward in monsoon modeling is presented.

2. Mean monsoon in CMIP3 models and its future projection

Of all the regional monsoon systems around the globe, the ASM is the most energetic and vigorous monsoon system dominating the global circulation during boreal summer. The seasonal cycle in solar forcing during spring-early summer (March through early June) results in the greater warming of the land in the Northern Hemisphere than the adjoining oceans. This is primarily related to the lower heat capacity of the land. The north-south thermal gradient due to land-sea thermal contrast induces a large-scale pressure gradient. Consequently, in the lower troposphere a strong cross-equatorial flow sets-up in the tropical Indian Ocean (Fig. 1c). This flow is instrumental in transporting the required moisture to feed the monsoon rainfall (Fig. 1a). The warm sea surface temperature (SST) in the northern Indian Ocean and tropical western Pacific (Fig. 1b) and the barrier layer beneath it maintain the deep monsoon convection (Shenoi et al. 2006). In retrospect, the in-situ heavy rainfall and river run-off maintain the barrier layer over the northern Bay of Bengal, and the cycle continues. Briefly, the coupled processes that determine the mean evolution of the ASM are varied and interactive.

Our current understanding is that the monsoon is an integral component of the climate system and is manifested due to ocean-land-atmosphere interaction. Therefore, our trust in projections of how the monsoon will respond to Earth's warming depends on the ability of the atmosphere-ocean general circulation models (AOGCMs) or alternately referred to as coupled models, in capturing the present-day monsoon climate and its complex space-time variations. The availability of the simulations with numerous global AOGCMs conducted recently for the third coupled model inter-comparison project (CMIP3) allows for analysis of the various facets of the ASM, namely, the mean monsoon precipitation, historical and projected variations in El Niño Southern Oscillation (ENSO)-monsoon coupling, monsoon onset, subseasonal variations and response of these aspects to global warming.

The simulation of regional monsoon precipitation climatology has proven to be rather difficult and therefore provides a severe test of the climate models. Modeling groups around the world have participated in many international programs to assess and examine the models' skill in simulating the mean monsoon in the atmosphere only models forced with observed SST (e.g., Sperber and Palmer 1996). Recognizing the fact that coupled processes are inherent for the monsoon, the output of 18 models used to simulate the climate of the

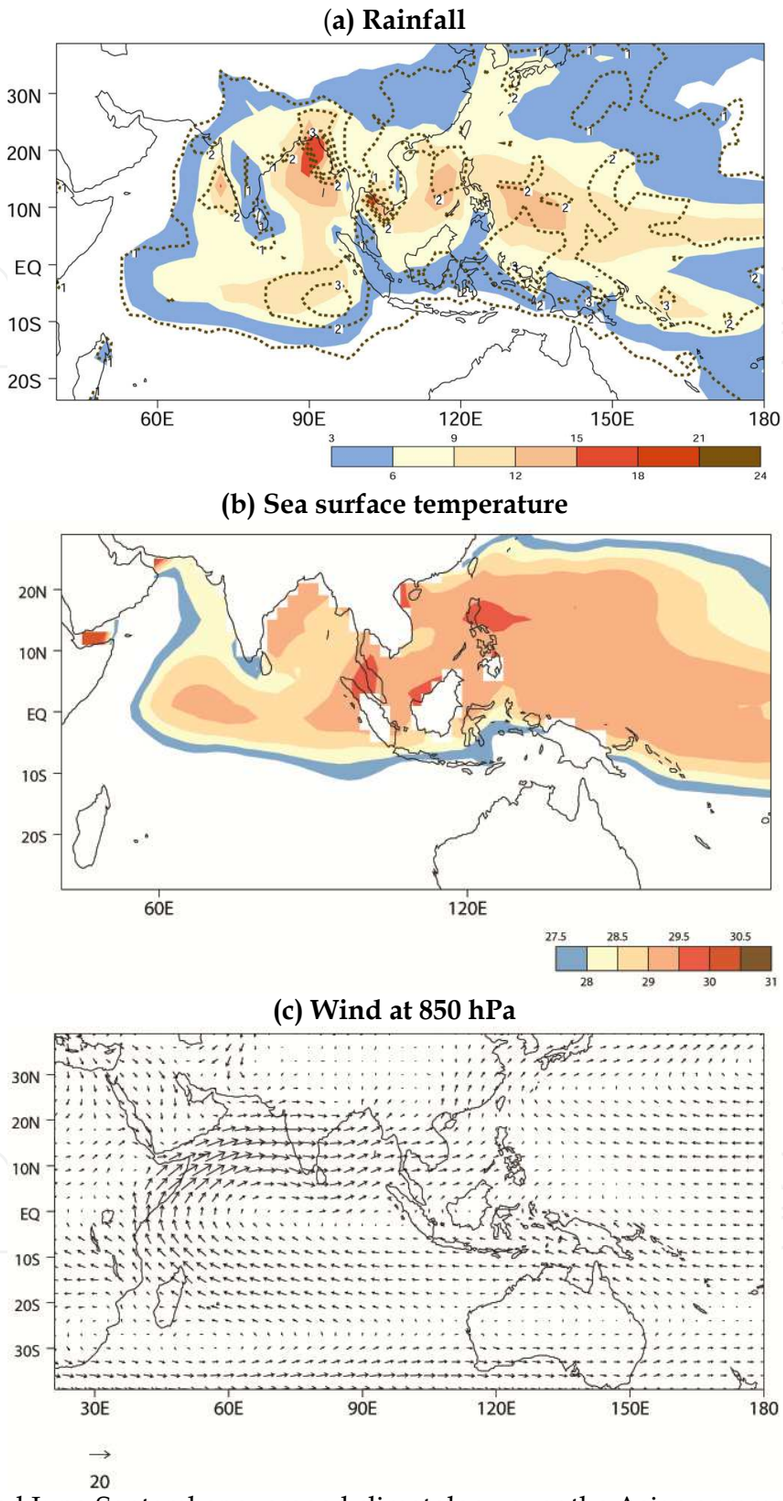


Fig. 1. Observed June-September averaged climatology over the Asian summer monsoon region: (a) precipitation (mm/day, shaded); (b) SST (oC), and (c) 850hPa wind (m/s). In (a) contours represent interannual standard deviations, and in (c) reference wind vector is also shown.

20th Century (20c3m) are examined. The 20c3m simulations attempt to replicate the overall climate variations during the period ~1850-present by imposing each modeling groups best estimates of natural (e.g., solar irradiance, volcanic aerosols) and anthropogenic (e.g., greenhouse gases, sulfate aerosols, ozone) climate forcing during this period. For each model, June–September averaged rainfall climatology of the last 30-years from the 20c3m simulations was constructed and compared with observations.

For climate scientists, one of the challenging issues is to identify and employ metrics in choosing models so that uncertainty in future monsoon projections can be reduced. While models are generally successful in capturing the large-scale circulation features, simulating the details in regional rainfall patterns and intensities are still in their infancy (Annamalai et al. 2007; Turner et al. 2007). Yet, modest progress has been made in recent decades. The observations (Fig. 1a) show that intense rainfall (> 6 mm/day) occurs over three regions in Asia, which represent (1) the Indian Summer Monsoon (ISM, 70°E–100°E, 10°N–25°N,) (2) the Western North Pacific Monsoon (WNPM, 110°E–150°E, 10°N–20°N), and (3) the eastern equatorial Indian Ocean (EEIO, 10°S–0, 90°E–110°E). Because these centers do not respond in unison to any internal or external forcing (Annamalai and Sperber 2005; Annamalai et al. 2007; Annamalai 2010), and influence each other at all time scales, a realistic representation of these three regional centers is needed if the models are to adequately project the future time-mean changes in rainfall as well as reproduce the variability of the monsoon. One metric based on the pattern correlations between simulated and observed rainfall estimates and their root mean square differences (RMSDs) for the chosen period indicated that only six models are capable of capturing the mean monsoon precipitation (Annamalai et al. 2007). The multi-model mean rainfall climatology constructed from averaging the climatology of these six models is shown in Fig. 2a. The agreement with observations in particular the representation of three regional rainfall centers is encouraging but diversity between model and observation still exists in the strength of rainfall over these regional centers. Therefore, in these models a large diversity in the projected intensity of monsoon rainfall is to be expected introducing uncertainties in future projections.

We are confident that due to anthropogenic forcing global mean surface temperature and associated water vapor will increase but large uncertainties exist in quantifying how various elements of the monsoon will respond to these changes. As mentioned above, due its low heat capacity land surface warming will be more pronounced over the land than the neighboring oceans, introducing a larger land-sea thermal contrast over the monsoon region. It is a well-accepted fact that sufficient land-sea thermal contrast is a necessary condition for the monsoon circulation to develop (Li and Yanai, 1996). Thus, consistent with the notion of rich-get-richer mechanism (Held and Soden 2006; Chou et al. 2009) one could expect monsoon rainfall to increase due to enhanced transport of moisture to South Asia from the tropical Indian Ocean (Kitoh et al. 1997; Meehl and Arblaster 2003; Stowasser et al. 2009; May 2010). Based on these arguments, most climate models do suggest for an increase in time-mean monsoon rainfall over tropical west Pacific and south Asia (Turner and Annamalai 2011). The projected rainfall changes over the tropical Indo-Pacific region from two CMIP3 models that both demonstrated realistic simulation of mean monsoon precipitation and ENSO-monsoon association (Annamalai et al. 2007; Turner et al. 2007) is shown in Figs. 2b-c. While both models indicate for an increase in rainfall over south Asia, the large diversity in the rainfall amplitude over the tropical Indo-Pacific region suggests the uncertainty in future quantitative projections. Despite both models experience similar

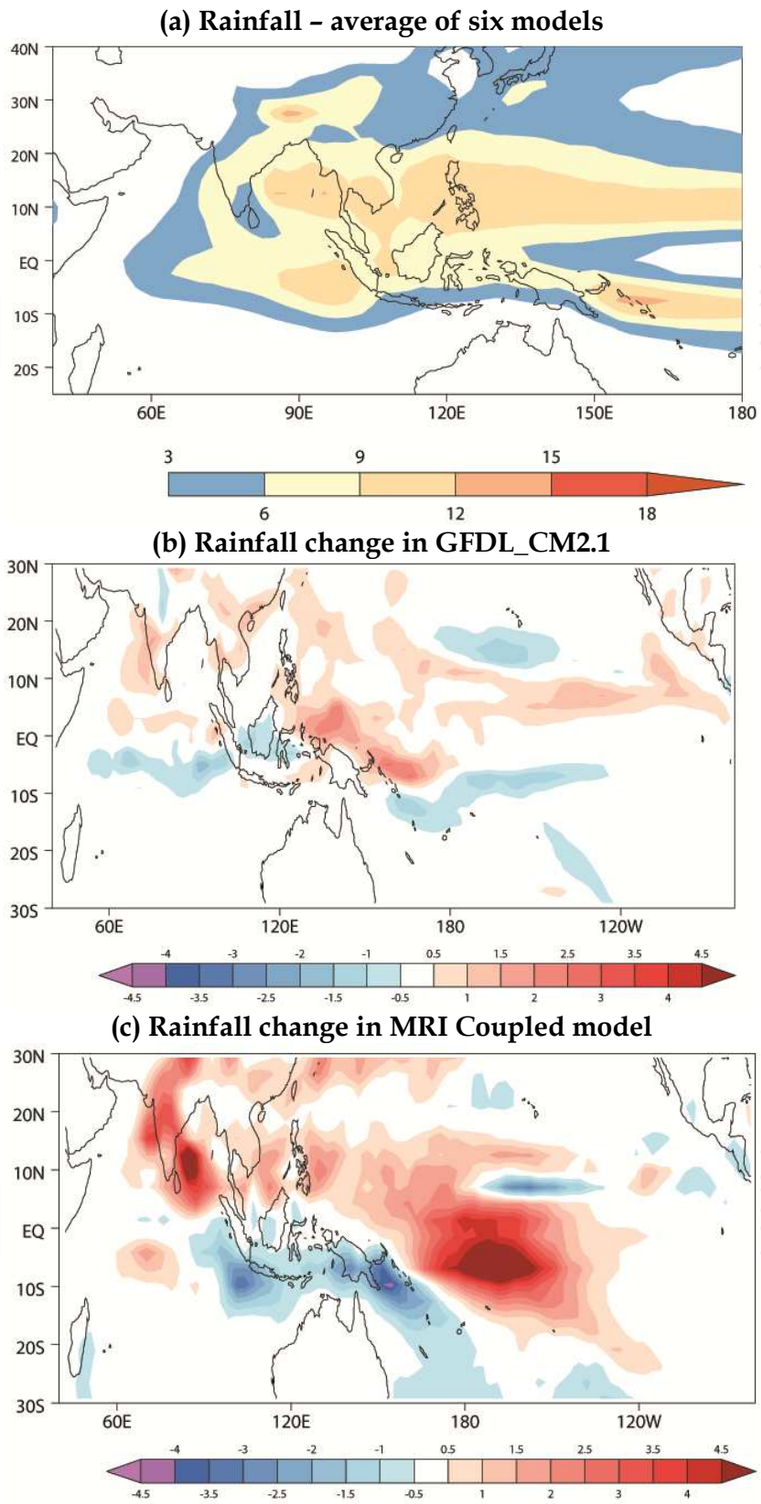


Fig. 2. (a) Mutli-model mean June-September precipitation (*mm/day*) climatology from 203m simulations; projected time-mean change in rainfall in doubled CO_2 simulations (1pccto2x minus 20c3m simulations), (b) GFDL_CM2.1 coupled model and (c) MRI coupled model

anthropogenic forcing in the historical simulations, significant rainfall differences imply the challenge in proper representation of important physical processes and their feedbacks in climate models. While moist convective processes and their interaction with circulation, role of mountains and their interaction with the flow, oceanic processes such as salinity and barrier layer over the warm pool of the Indo-Pacific are few elements that are thought to influence the monsoon (as mentioned above) but realistic representation of all these interactive processes in a model is a demanding task for climate scientists.

Due to the presence of multiple regional heat sources and their interaction (Stowasser et al. 2009), the simulated monsoon response to anthropogenic forcing is not that simple where rainfall increases despite a weakened monsoon circulation (Kitoh et al. 1997; Udea et al. 2006). Stowasser et al. (2009) argued that the reduced rainfall over the equatorial Indian Ocean rainfall (Fig. 2b) forces a low-level anomalous circulation that opposes the climatological cross-equatorial flow (Fig. 1b) but the reduced circulation is richer in moisture resulting in an increase in rainfall. They highlighted that changes in time-mean circulation, through local air-sea interaction, are instrumental in anchoring SST warming over the Arabian Sea and subsequent increase in evaporation. It is suggested that to understand the monsoon response to anthropogenic forcing a clear understanding and quantification of dynamic and thermodynamic feedbacks are necessary. While most models capture the thermodynamic feedbacks (rich get richer mechanism), realistic representation of dynamic feedbacks in climate models will require realistic simulation of regional heat sources.

3. Monsoon variability

In this section, we start with year-to-year variations in the seasonal mean monsoon rainfall that accounts for floods and droughts (Section 3.1), followed by monsoon onset (Section 3.2), and end with subseasonal variations (Section 3.3). In all subsections, we will briefly review the models' ability in simulating these aspects in the current climate and discuss their future projections.

3.1 Interannual variability

One of the major components of the ASM is the Indian Summer Monsoon whose strength is often represented by the all-India Rainfall (AIR) index. From historical record, the observed AIR departures from seasonal mean are shown in Fig. 3a. While droughts (years of rainfall below 1 standard deviation) and floods (years of rainfall above 1 standard deviation) are clearly noticeable, there is a tendency for droughts (e.g., 1871, 1877, 1963; 1972) and floods (e.g., 1988), to occur during ENSO years. A similar rainfall time series from a coupled model simulation for the 20th century (Fig. 3b) also suggests that occurrence of droughts and floods are more common during ENSO years. It needs to be mentioned here that since the seminal work of Walker (1924) and Walker and Bliss (1932) the contemporaneous SST anomalies in the central-eastern Pacific associated with ENSO have been the predominant forcing of the AIR variability supporting the hypothesis that slowly varying boundary conditions exert a significant impact on monsoon variability (Charney and Shukla, 1981). In particular, both in observations and in a coupled model Pillai and Annamalai (2011) noted that all severe weak and strong monsoons are associated with the developing phase of ENSO. While a weakening in the ENSO-monsoon association in recent decades (Shukla 1995) was

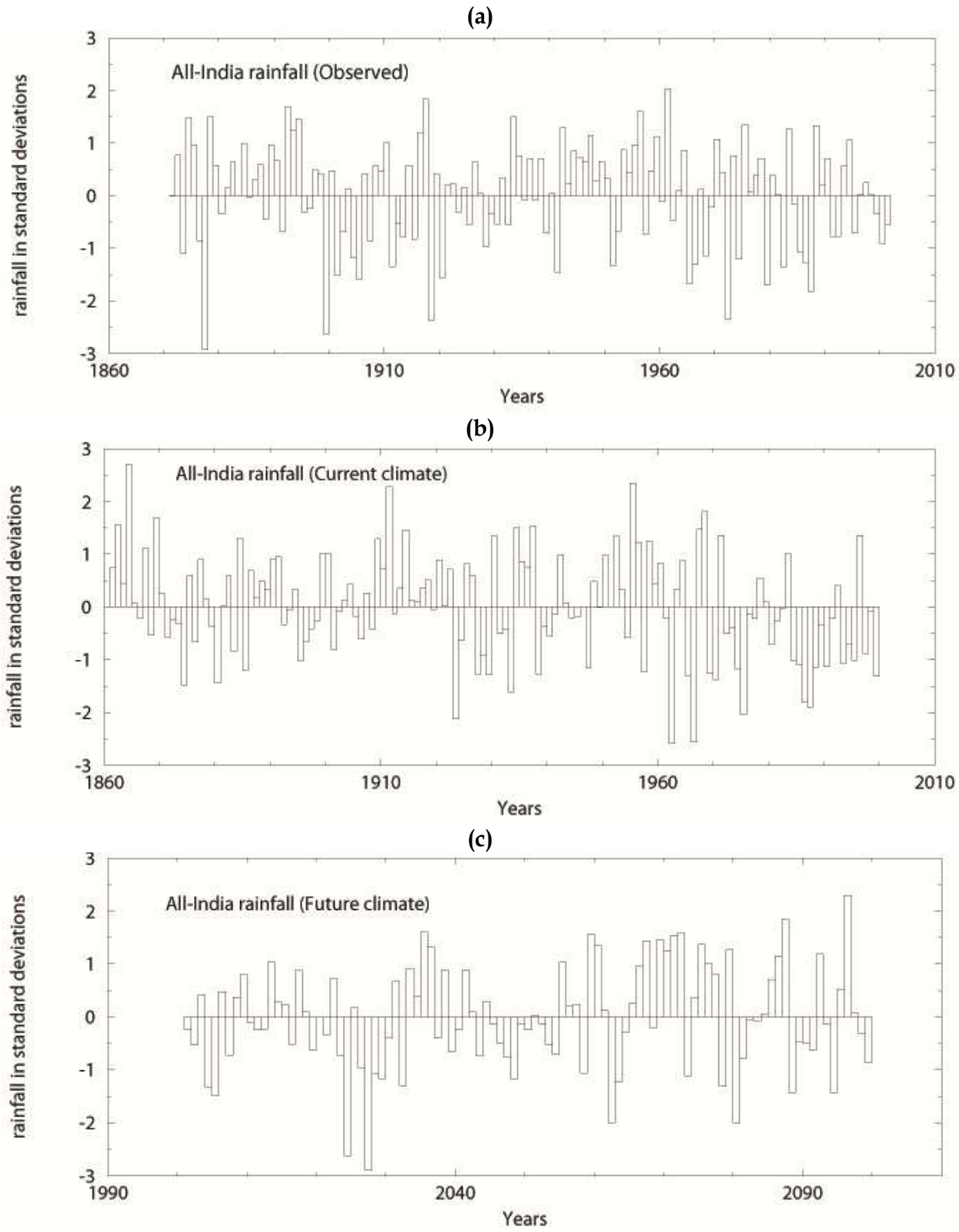


Fig. 3. Interannual variations in monsoon rainfall over India: (a) observations;
(b) GFDL_CM2.1 simulated current climate, and (c) same as (b) but for future climate.

attributed to global warming (Krishnakumar et al. 1999), one emerging result from coupled modeling studies is that the ENSO-monsoon association remains intact in a warmer world (Annamalai et al. 2007; Turner et al. 2007). Given the large diversity in the simulation of ENSO characteristics in CMIP3 models (Achcutha Rao and Sperber 2006; Joseph and Nigam 2006), uncertainty exists in the projection of monsoon interannual variability. However, while the magnitude of interannual standard deviation of monsoon rainfall depends on ENSO variance, the frequency of droughts and floods may not be influenced as shown next. Fig. 3c shows monsoon interannual variability as simulated by a coupled model when subjected to doubled CO_2 forcing. While droughts and floods do occur in a warmer world, there is no clear suggestion for them to either increase or decrease. This result is consistent with that of Turner and Annamalai (2011) suggesting that the monsoon is a very robust system. As in observations (Fig. 3a), both in the current and future climates, there is a tendency for decadal clustering of monsoon floods and droughts (Figs. 3b-c), a feature that is perhaps unrelated to global warming (Annamalai et al. 2007).

3.2 Onset

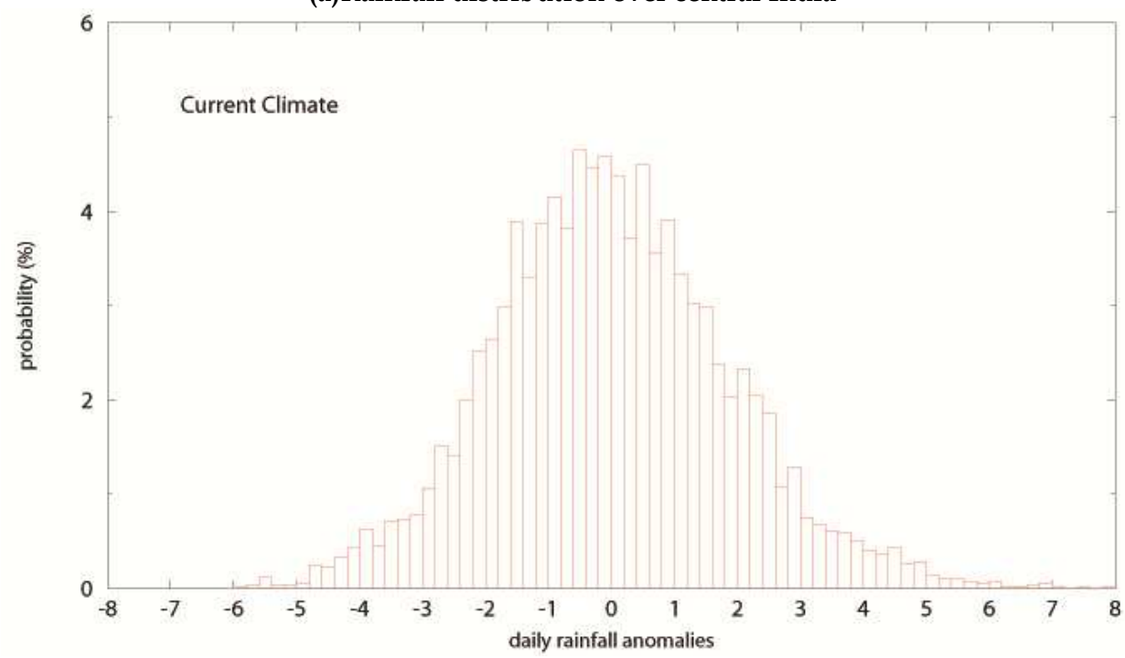
One of the spectacular aspects of the monsoon is its onset. Usually, the monsoon rains and associated moisture laden winds first hit the plains of Indo-China and gradually move westwards. Over India, the monsoon rains usually arrive at the southern state of Kerala around 01 June with an interannual variations of about 7 days. The monsoon onset is closely monitored because it offers remedy from pre-monsoon heat waves, sets the pace of agricultural practices such as soil moisture increase and sowing period, and drinking water needs. Under anthropogenic forcing, if one expects stronger land-sea thermal contrast and abundant moisture then a natural question is: Will the monsoon onset occur earlier and with greater intensity? If so, will the rainfall amount during the onset spell lead to changes in agricultural practices? For instance, if the onset is accompanied with heavy rainfall leading to soil erosion and run-off, what measures need to be taken to avoid loss in farming?

Annamalai et al. (2007) analyzed the CMIP3 models to check if the onset occurs earlier in a warming world. Their findings suggest that models that realistically simulate current monsoon precipitation climate, project an enhanced land-sea thermal contrast between the Indian land-mass and the southern Indian Ocean in the range of ~1.5 – 3°C. They noted that the MRI coupled model with strongest gradient suggests onset 2-3 pentads earlier and a 15% increase in rainfall strength (Fig. 2c) while the model with moderate gradient suggests a delayed onset. This suggests that factors other than land-sea thermal contrast plays important roles and thus introduces uncertainty in our projections of change to the monsoon onset. One such candidate is that feedback between dynamics and moist convection anchors the onset process, and therefore how moist process are represented in models will perhaps determine the onset dates.

3.3 Intraseasonal variability and extreme events

Rainfall during the summer monsoon is not steady, consisting of a sequence of active and break periods, one cycle of which lasts 40−60 days. During the ASM season there are two preferred locations of convection over the Indian longitudes, over the continent and over the equatorial Indian Ocean (Fig. 1a). The transition of convection from its oceanic to continental regime often involves intraseasonal northward propagation over India and the Bay of Bengal (Yasunari 1979). Similar north-northwestward migration of convection is also

(a)Rainfall distribution over central India



(b) Rainfall distribution over central India

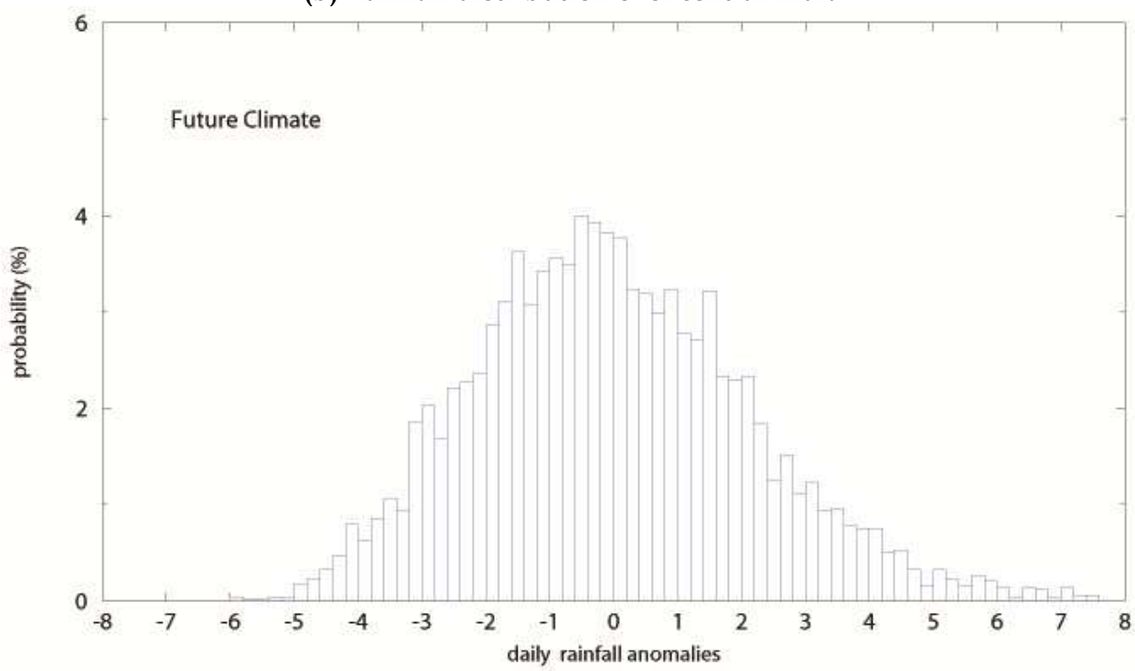


Fig. 4. Probability of occurrences of active and break events over central India as simulated by GFDL_CM2.1 coupled model: (a) current climate (1961-2000), and (b) future climate (2061-2100)

observed over the western Pacific (Annamalai and Slingo 2001). These northward components co-exist with the eastward propagating Madden-Julian oscillation (MJO), and they encompass the boreal summer intraseasonal variability (BSISV). For climate models to project the future

behavior of extended monsoon breaks (breaks or lull in rainfall lasting for 7 days or more) and extreme rainfall events (daily rainfall exceeding 120.0 mm/day), it is a pre-requisite that they capture the space-time evolution of BSISV, as well as monsoon synoptic systems (discussed below). Sperber and Annamalai (2008) examined the ability of CMIP3 models in capturing BSISV and noted that almost all of them (with various degrees of fidelity) simulated the equatorial component over the Indian Ocean with appreciable intensity of convection, a feature absent in models forced by observed SST (Waliser et al. 2003). It is argued that realistic simulation of equatorial component is a pre-requisite for BSISV simulation. Of the models, the GFDL_CM2.1 shows reasonable skill in capturing the poleward propagation of rainfall over the Indian longitudes, while all others have limitations (Sperber and Annamalai 2008). Turner and Slingo (2009) noted that both active and break events will become more intense (wetter and drier respectively relative to the seasonal cycle) consistent with general intensification of tropical rainfall. A simple histogram of daily rainfall anomalies averaged over central India for current (Fig. 4a) and future climate (Fig. 4b) by the GFDL_CM2.1 coupled model does suggest that probability of less intense breaks (anomalous rainfall less than 2-3 mm/day) is expected to decrease in a warmer world but heavy rainfall events (anomalous rainfall greater than 6-8 mm/day) increase only marginally. While the news that extreme rainfall events do not increase dramatically is encouraging, the limitations are that coarse model resolutions employed in climate models may not be adequate enough to capture the genesis and intensification of monsoon depressions (as discussed below) and also that intensity of mean monsoon rainfall over central India is not represented realistically in climate models.

At sub-seasonal time scales, synoptic systems such as monsoon depressions form over the quasi-stationary seasonal monsoon trough. During the peak monsoon season (July-August), a majority of them form over the warm waters of northern Bay of Bengal, and move in a west-northwesterly direction, and in most places over central India, almost all extreme rainfall events there are attested to depressions (Sikka 2006). Therefore, to know the future changes in the number extreme rainfall events, it is important to examine climate models' projections in the depressions' strength. Stowasser et al. (2009) examined synoptic systems in ECMWF Reanalysis (ERA-40) products and output from selected CMIP3 models that showed skill in simulating the mean monsoon precipitation (Fig. 2a). The monsoon synoptic systems thus identified were then analyzed as a function of maximum wind speed and as the number of 12-hour time-steps each system was present in the domain. The frequency distributions of maximum storm speed for the *20th century* GFDL model runs (blue bars) over the larger domain (Figure 5a) and over only the Bay of Bengal (Figure 5b) are asymmetric. The distributions peak around 12 m/s after which they fall off rapidly. The model simulates very few intense storms (wind speed > 15m/s). In summary, of the AOGCMs analyzed, the CM2.1 coupled model captures, in relative terms, the mean monsoon precipitation and the spectrum of its variability realistically. But the coarse resolution global model does not project any increase in the depressions strength. Is it due to the limitation in model resolutions that the genesis and intensification of synoptic systems are not well represented? To address this, a high-resolution regional climate model study was undertaken. Using CM2.1 lateral boundary conditions, the current and future climate (i.e., $4xCO_2$) states were simulated at 100 km resolution by a regional model developed at the International Pacific Research Center (IPRC-RegCM). The simulated storms from this regional model indicate that those with intense magnitude (blue bars in Fig. 5 bottom panel) become much stronger (red bars in Fig. 5 bottom panel). These results would then suggest for the possible occurrence of more extreme rainfall events over central India. However, this result is from one model and therefore needs to be confirmed with other regional model experiments.

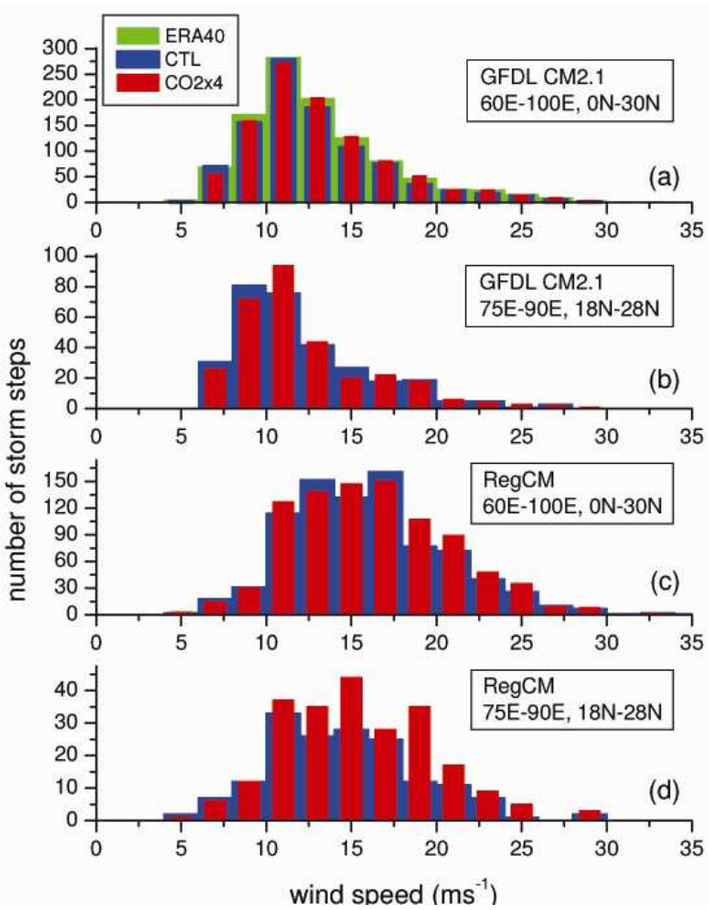


Fig. 5. Frequency distribution as a function of maximum wind speed of each synoptic system estimated for the entire northern Indian Ocean (a and c), and only over Bay of Bengal (b and d): Panels (a) and (b) results from CM2.1, and panels (c) and (d) results from IPRC_RegCM. The blue bars indicate the control runs (CTL) and the red bar the 4xCO2 (four times increase in CO2 forcing) integrations, respectively. The frequency is given in numbers of 12h time-steps a system was present in the domain (adopted from Stowasser et al. 2009).

4. Sources of uncertainties

Climate scientists depend on models that incorporate sophisticated understandings of the coupled behavior of the climate system. The fact that these models reproduce the time evolution of global mean temperature over the last century provides credibility. However, whether at global or regional scales uncertainty in the model precipitation projections still exist. Here, we summarize the most relevant sources of uncertainties that hamper our confidence in climate model projections.

The leading factor is perhaps cloud feedback. Briefly, the changes in atmospheric temperature lead to increase in water vapor content that subsequently results in changes in cloud properties. It is well known that water vapor is the most dominant variable in influencing green house effect (more effective than CO_2). Therefore, how the changes in cloud properties influence the Earth's energy balance and how that feedback loop operates is poorly understood and hence difficult for climate models to handle. Second, apart from increases in

CO_2 concentrations, increases in black carbon aerosols (or soot) in recent decades in the Northern Hemisphere and in particular over the ASM region pose another source of uncertainty. Depending on their concentration and vertical distribution, the aerosols either absorbing or scattering influence the radiation budget in a complex way. For example, both scattering and absorbing aerosols reduce the solar insolation reaching the surface. Over the ASM region, reduced solar insolation tends to reduce the land-sea thermal contrast, and thereby weaken the monsoon circulation. On the other hand, absorbing aerosols warm the lower atmosphere and can induce a stronger monsoon circulation. Undoubtedly aerosols add a source of uncertainty in model monsoon projections (Menon 2004). In summary, we are unsure of how much warming due to greenhouse gases has been cancelled by cooling due to aerosols, and to what extent the future projections are influenced by systematic errors in climate models. Thus, the magnitude of global warming in the next century is very uncertain, and thus the response of the monsoon and its variability across all time scales are bound to have large uncertainties. Above all, monsoon itself is a very complex phenomenon to model.

While uncertainty glooms for future monsoon projections, it is important to recognize that human practices may add to its future behavior. While it may not be important for humans to influence a single monsoon depression but can and do have a long-term influence on the climate that causes the depression. For instance, land-use changes in agricultural practices can potentially influence the surface energy balance and can have a direct impact on the regional atmospheric circulation and rainfall. Since the industrial revolution, hard observed evidences are available for increased burning of fossil fuels and subsequent increase (about 30%) in the concentration of CO_2 in the atmosphere. The booming economy in many countries means that more demand for better quality of life that include improved transportation, industrial expansion and so on – all elements capable of enhancing the CO_2 levels. While human civilization does influence the global and regional climates, it is rather difficult to predict the future human practices and thus emission scenarios causing another source of uncertainty.

It is a challenge for climate researchers to address the uncertainties and provide accurate projections to the policy makers. The uncertainty has contributed to disagreement between groups that want immediate action and reduce GHGs emissions and develop adaptation measures, and those who want to wait and watch. While the debate on uncertainty prevails, policy makers need to focus on adaptation measures. The confidence on scientific evidence on the magnitude of long term changes in climate is expected to increase in the next two decades but the ongoing changes in the frequency and intensity of certain weather events such as tropical cyclones have already raised the concern to develop adaptation measures One way the climate scientists adopt to reduce uncertainty is to produce climate projections from many different climate models, and provide a range of possible outcomes. Based on them, identifying a set of policies for practical solutions will have far reaching implications.

5. Summary

It is now recognized that any future predictions or projections of long-term changes in climate can only by made by complex climate models that depend on super computers. While the last 2 decades have witnessed a phenomenal advancement in computing facilities and access of climate model data (Meehl et al. 2007) predicting or projecting the regional features that are directly relevant to humans and policy makers need ultra supercomputers that are not currently available. The world modeling summit held in May 2008 argued that "climate models will, as in the past, play an important, and perhaps central role in guiding

the trillion dollar decisions that the peoples, governments and industries of the world will be making to cope with the consequences of changing climate" (Shukla et al. 2009). The summit called for "Governments should work together to build the supercomputers needed for future predictions that can capture the detail required to inform policy".

It is fair to say that in climate science there is no bigger problem than modeling the monsoons. Even after the availability of super computers, there are many other factors that will limit our ability to model the monsoons. While the importance of large-scale forcing such as orography and boundary forcing such as SST are fairly understood (Hoskins and Rodwell 1995; Charney and Shukla 1981), how the various moist processes interact among them, as well as the specific role of oceanic processes responsible in shaping the mean monsoon precipitation and its spectrum of variability are just beginning to unfold. The slow progress in modeling the monsoon is perhaps due to lack of quality and sustained observations over the monsoon region including that over the tropical Indian Ocean. It is important to have 3-dimensional observational network to monitor the horizontal and vertical extent of moist processes, careful monitoring of evaporative processes over the tropical Indian Ocean, and check the changes for SST threshold for the occurrence of deep convection are some of the observational program to be given priority. At the same time, improvements in model physical parameterizations are continually getting improved. Both new observational information with model improvement needs to go hand-in-hand for making progress in monsoon modeling. Another stumbling factor is that the monsoon itself is a complex phenomenon and poses a monumental challenge for climate scientists.

While we are confident that global hydrological will intensify in a warmer atmosphere, any future projections of regional rainfall changes have large uncertainties. This is because, our current understanding of the various physical processes and their feedback in the climate system is limited to make any significant progress in the prediction of future climate change at regional spatial scales. One of the major uncertainties is due to cloud feedback. Briefly, the changes in atmospheric temperature lead to increase in water vapor content and that subsequently increases changes in cloud properties. It is well known that water vapor is the most dominant variable in influencing green house effect (more effective than CO_2). Therefore, how the changes in cloud properties influence the Earth's energy balance and how that feedback loop operates is poorly understood and hence difficult for climate models to handle. Efforts are underway to bridge this gap, and it is expected that with the availability of ultra supercomputers and very high resolution (e.g. cloud resolving) models the future changes in regional climate can be predicted with an uncertainty envelope that will be useful for policy making.

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
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Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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