Advancing Indian Monsoon Rainfall Predictions

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ABSTRACT

Despite great strides made in seasonal climate forecasting using dynamical models, skill in predicting the Indian monsoon is woefully poor. Our analysis of the reasons for failure exposes a flaw in the popular design of dynamical prediction systems. The approach of driving atmospheric models with a projected ocean surface temperature presupposes Indian monsoon variability to be a consequence solely of the atmosphere reacting to the ocean. We demonstrate significant improvements in the skill of Indian monsoon predictions when atmospheric models are coupled to, and fully interactive with the ocean. The additional feedback of the atmosphere onto the ocean is thus deemed critical for harvesting skilful monsoon predictions.

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Forecasting Indian summer monsoon rainfall has an unparalleled lineage within the history of climate prediction. Routine efforts were born of the great 1877 Indian famine that resulted from failed monsoon rains. Subsequent statistical models based on correlation methods developed by Sir Gilbert Walker (Walker, 1924) form the foundation of modern Indian monsoon predictions (Hastenrath, 1991; Krishna Kumar et al. 1995). Such empirical approaches are skilful, and have now been placed upon a firm physical basis owing to abundance of observations on the land, ocean and within the free atmosphere (Shukla, 1987; Rajeevan, 2001). Such progress notwithstanding, notable failures in Indian monsoon rainfall forecasts for recent years (Gadgil et al. 2002) compel an assessment of the prospects for new prediction methods.

Year-to-year swings in monsoon rainfall are linked to global forcing functions that evolve slowly compared to the length of the monsoon season itself, and oceanic effects appear to be primary sources (Charney and Shukla, 1981; Palmer, 1994; Webster et al. 1998). A popular question is the prospect for monsoon forecast skill based on dynamical models in which ocean conditions are perfectly known, and are specified (Gates et al. 1998; Sperber and Palmer, 1996; Gadgil and Sajani, 1998; Kang et al. 2002). It is widely believed that the skill of such simulations is a useful metric for the upper bound in achievable skill using dynamical approaches.

Our own analysis of atmospheric general circulation model (AGCM) simulations in which the actual sea surface temperatures (SSTs) have been prescribed suggest high prospects for furthering Indian monsoon prediction skill. We calculate Indian summer monsoon rainfall predictability in 10 different AGCMs[1] based on 50-year long integrations beginning in 1950 in which the models are forced with observed monthly varying global SSTs (commonly referred as GOGA runs). Ensemble methods are used in which individual runs differ by their atmospheric initial conditions, but employ identical observed SSTs as lower boundary forcing. The availability of large ensemble sizes permits an analysis of 'perfect model' skill, in addition to a calculation of actual simulation skill. The former is measured by the 50-year averaged correlation between June-September Indian monsoon rainfall[2] occurring in one model realization with that occurring in individual parallel runs of the same model. The results for all models are summarized by plotting the probability density function (PDF) of correlations (Bowman and Azzalini, 1997).

As shown in Fig. 1 (red curve), a 0.65 median correlation indicates that over 40% of the year-to-year Indian monsoon rainfall variations are oceanic controlled, arguing for a high predictability within this ‘perfect model’ scenario. Note further that a large majority of the individual model skill estimates exceed an estimate of skill using empirical methods (Fig. 1, black dashed line[3]). Such high correlation skill indicates the AGCMs’ 50-year Indian summer monsoon rainfall time history is highly reproducible from one integration to another. Predictability in this

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[1]The models used and their ensemble sizes are: 1. MPI-ECHAM4 (24), 2. MPI-ECHAM3 (10), 3. GFDL –AM2 (10), 4. NASA (9), 5. Scripps-ECPC (7), 6. NCEP (13), 7. ARPEGE (8), 8. NCAR-CCM3(12), 9. NCAR-CAM2 (15) and 10. GFDL R30 (4). The models typically have a ~300km horizontal resolution.

[2]Monsoon rainfall from the models is the total rainfall over 8-30N and 70-90E.

[3]The skill of empirical models is taken to be the correlation between observed monsoon rainfall (June-September) and the simultaneous NINO3.4 index, defined as SSTs averaged over 5ºN-5ºS and 170ºW-120ºW. Observed monsoon rainfall index (Parthasarathy et al. 1994) is available from (http: //www.tropmet.res.in).

perfect model scenario is thus ostensibly judged to be high to the extent the SSTs could themselves be accurately forecast.

However, we find the actual simulation skill of Indian monsoon rainfall to be woefully inadequate. The 1950-1999 temporal correlation between each of our 10 models' ensemble mean Indian monsoon rainfall and observations is computed, and is again summarized with a PDF (Fig. 1, blue curve). The near-zero median value indicates that the AGCMs explain virtually none of the observed Indian monsoon rainfall variations, and thus their skill is effectively zero. This corraborates the experience of climate prediction centres that have recently reported little skill in their dynamical attempts to foretell Indian summer monsoon rain (Barnston et al. 2003, Goddard et al. 2003). Their practice employed a two-tier approach in which the future state of global SSTs were first predicted, and then specified as boundary forcings for AGCM integrations. It is now evident that their low skill is not due to poor forecasts of the SST states themselves – since low skill also occurs when the actual observed global SSTs are specified.

It is evident that the high, theoretical perfect model skill scores are not being achieved. Comparison of AGCM (Fig. 2, top) and observed (bottom) monsoon season rainfall and surface temperature anomalies during El Niño/Southern Oscillation (ENSO) illustrates a characteristic feature of model failure. Much of India suffers drought during ENSO's warm phase (bottom left). Anomalously warm surface temperatures coincide with this drying over the sub-continent and adjacent sea (bottom right), conditions known to result from the atmospheric feedback by anomalous winds that act to suppress rainfall (Klein et al 1999; Alexander et al. 2002). Not only does the AGCM fail to reproduce Indian drought, it actually generates a large-scale increase in rainfall over the warmest SSTs of the Indian Ocean and Arabian Sea (top left). It is our contention that this misrepresentation of air-sea energy exchange, also identified in other model studies, is directly responsible for degrading skill (Clemens and Oglesby, 1992; Kumar and Hoerling, 1998).

Various other theories have been proposed to explain such low skill. One involves poor simulation of the Indian monsoon mean climate (Sperber and Palmer, 1996; Gadgil and Sajani, 1998). We, however, do not find a strong relation between simulation skill and the realism of the mean climatology for the 10 AGCMs studied herein. Another possibility is an inability of the AGCMs to realistically simulate the ENSO-Indian monsoon statistical relation (Lau and Nath, 2000; Wu and Kirtman, 2004). We find that the absence of simulation skill among the 10 AGCMs cannot be explained by an absence of an ENSO link, and in fact several of the poor performing AGCMs possess realistic ENSO-Indian monsoon relations.

Instead, we discover skill can be materially increased by treating the year-to- year swings in Indian monsoon rains as a coupled ocean-atmosphere problem. Such interactions are not represented in atmospheric GCMs wherein the two-tiered design presupposes Indian monsoon variations to be described as a purely forcing-response system. This popular approach to Indian monsoon forecasting masks the true skill of dynamical models since it is calculated for a fictitious system in which air-sea interactions exist for sea-to-air only. The absence of simulation skill in the AGCMs (Fig. 1, blue curve) is thereby unlikely to be an accurate measure for the prospects of dynamical monsoon predictions.

In a companion set of experiments using one of the general circulation models, SSTs in the tropical eastern and central Pacific are specified as before for 1950-1999, but SSTs elsewhere in the World Ocean are free to evolve according to coupled air-sea interactions with a mixed layer ocean model (MLM). These simulations thus retain the ENSO variations. SST variations over the so-called "warm pool" reaches of the Indian Ocean and seas adjacent to Asia are permitted to interact fully with the fluctuating monsoon circulation system. More details on this 16 member ensemble MLM simulations can be found in Lau and Nath (2003). The scatter diagrams of Fig. 3 (right) compare the 50 years of modelled versus observed Indian summer monsoon rainfall using both uncoupled (top) and coupled (bottom) approaches. The relationship is virtually random in the uncoupled simulations, and the average correlation skill is -0.02. A strong linear relationship emerges in the coupled simulations, and the skill increases to +0.43. This significant change in skill is highlighted by the magenta circles and arrow in Fig. 1, and it can be seen that the coupled model skill now exceeds those of each of the 10 AGCMs[4].

The spatial plots of Fig. 3 illustrate the (1950-1999) correlation between Indian summer monsoon rainfall and SSTs in the uncoupled model (top-left), the coupled model (middle-left), and the observations (bottom-left). The large-scale pattern has not greatly changed by introducing coupling in this particular model. One can discern, however, a change in SST correlations over the Arabian Sea and Bay of Bengal in the coupled model that now agree more closely with observations. This re-emphasizes that the realism of ENSO-monsoon relations alone is an insufficient condition for realizing predictive skill, and that correct treatment of local warm pool air-sea interactions is of great importance.

We are able to confirm the robustness of these findings with a second set of identically designed coupled experiments (12 runs), except using a different AGCM and employing an even simpler mixed layer model (Giannini et al. 2004). The

[4]All possible combinations of ensemble size 4 are drawn from the 16 member MLM runs. The 4-member ensemble mean of each combination is correlated with the observed rainfall. The 5th and 95th percentile of the resulting correlation coefficients form the confidence interval. The correlation coefficient from the 4 run sample of uncoupled GOGA falls outside of this interval, indicating that the increase in correlation in the MLM runs is independent of ensemble size.

atmospheric component of this system is the one corresponding to the AGCM having the worst relation with observed Indian monsoon rain variations among the 10 studied. The scatter diagrams (Fig. 4 right panels) reveal a dramatic change in skill, from –0.27 in the uncoupled model to +0.22 in the coupled model (also indicated in Fig 1 by the dark green circles and arrow). This is associated with a tropic-wide reversal in the Indian monsoon-SST relationship (Fig. 4 left panels). Wet (dry) Indian monsoon rainfall years in the uncoupled model occur in tandem with warm (cold) SSTs adjacent to the subcontinent and across the ENSO region, opposite to that occurring in nature (Fig. 4 top-left). This correlation structure is rectified by introducing coupling (Fig. 4 bottom-left). It is also noteworthy that the monsoon rainfall-SST correlations are very similar between the two coupled models (cf Figs. 3 and 4), whereas they were virtually out-of-phase between their uncoupled AGCM counterparts.

Our results reveal that the ENSO contribution to Indian monsoon skill can be masked in AGCMs, most probably by misrepresenting air-sea interactions over the warm pool regions of the Indo-West Pacific Ocean. The warming (cooling) of the Indian Ocean, Arabian Sea, and Bay of Bengal during El Niño (La Niña) is typically associated with reduced (increased) cloud cover; yet such SST anomalies prescribed in AGCMs tend to excite increased (decreased) cloud cover and convection that encompass the adjacent continent. During warm ENSO events, surface evaporation over the anomalously warm western Indian Ocean and Arabian Sea is observed to decrease due to the weakened monsoon winds, yet is simulated to increase in the AGCMs due to increased upward fluxes resulting from the specified warm SSTs. This provides an additional erroneous moisture source for monsoon rains (Clemens and Oglesby, 1992). The specified warm pool SSTs in AGCMs thus yield an unrealistically strong negative feedback on the monsoon that competes with the remote ENSO influence as reported in other recent studies (Lau and Nath, 2000; Wu and Kirtman, 2004; Wang et al. 2004). The practical implication of our study is the ensuing complete forfeiture of skill using uncoupled dynamical approaches. Skill can be dramatically recovered by even simple treatments of the coupled nature of air-sea interactions using mixed layer ocean models. A systematic intercomparison of monsoon predictability throughout the tropics in coupled and uncoupled models, and a re-evaluation of dynamical methods, thus is clearly required.

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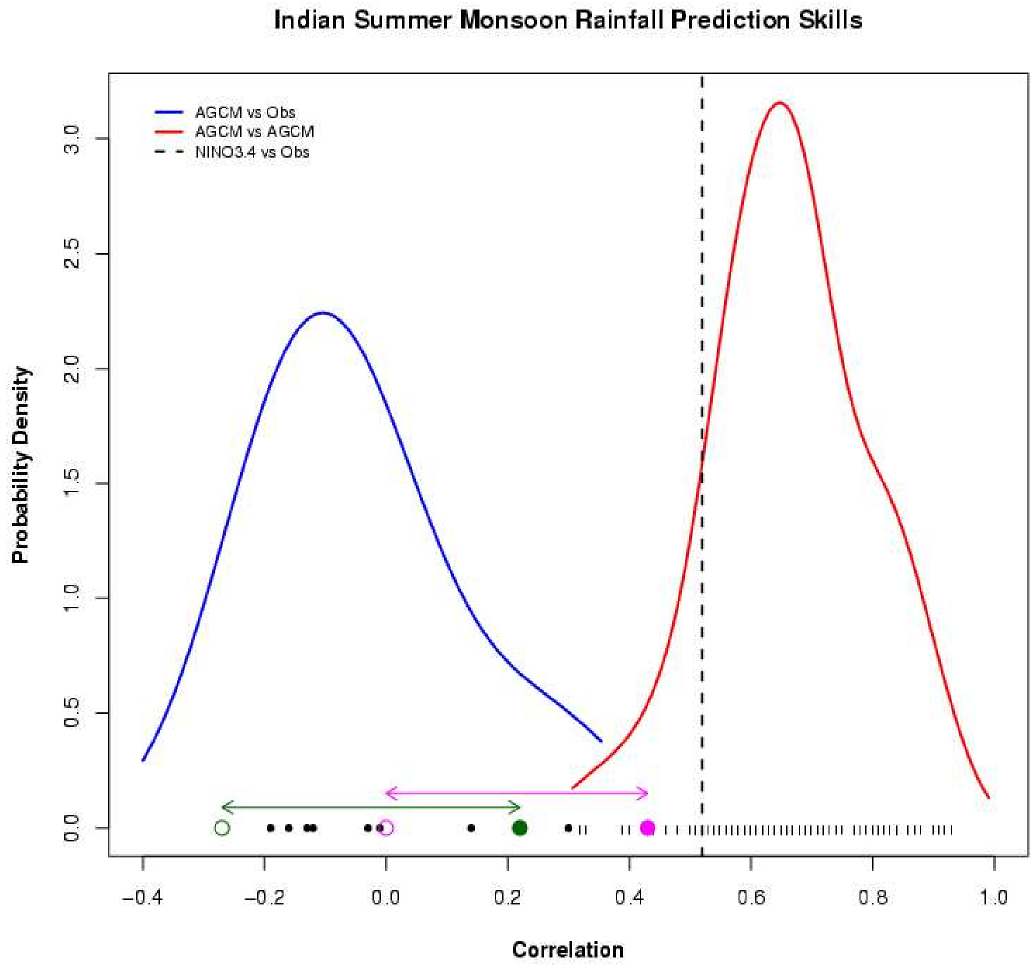
Figure Captions:

Figure 1. Probability density functions (PDFs) of correlation skill of June-September Indian monsoon rainfall based on a theoretical 'perfect model' analysis (red curve), and based on the actual skill compared to observed all Indian monsoon rain (blue curve). Analysis is based on 10 AGCMs forced with specified global SSTs of 1950-1999. Tick marks denote the correlation between individual model realizations on the 1950-1999 Indian monsoon rain time series. Circles denote the correlation between ensemble GCM and observed Indian monsoon rain times series. Closed, colored circles denote the skill of two of the AGCM coupled to a mixed layer model. Arrows denote the change in skill between pairs of uncoupled and coupled GCM simulations.

Figure 2. Monsoon season June-September warm minus cold El Niño/Southern Oscillation climate signals of, (**A)** ensemble mean rainfall from NCAR/CCM3 AGCM, (**B)** same as A but for surface temperatures, (**C)** Same as A but for satellite estimated rainfall derived from outgoing long-wave radiation (OLR) (**D)** same as B but for observed temperature. Note that SSTs have been prescribed in the AGCM. Period of analysis is 1950-1999, except 1975-2002 for OLR.

Figure 3. Correlation maps of (**A**) observed SSTs and monsoon rainfall simulated from uncoupled GFDLR30 (GOGA) model, (**B**) simulated SSTs and monsoon rainfall from the coupled (MLM) model, (**C**) observed SSTs and observed rainfall. Scatter plots of standardized anomalies of observed and simulated monsoon rainfall for each year during 1950-1999 from GOGA and MLM are shown in (**D**) and (**E**), respectively. Note that in the coupled model, SSTs have been prescribed between 15ºN-15ºS and 172ºE-80ºW.

Figure 4. Correlation maps of (**A**) observed SSTs and monsoon rainfall simulated from uncoupled NCAR-CCM3 (GOGA) model, (**B**) simulated SSTs and monsoon rainfall from the coupled (MLM) model. Scatter plots of standardized anomalies of observed and simulated monsoon rainfall for each year during 1950-1994 from GOGA and MLM are shown in (**C**) and (**D**), respectively.



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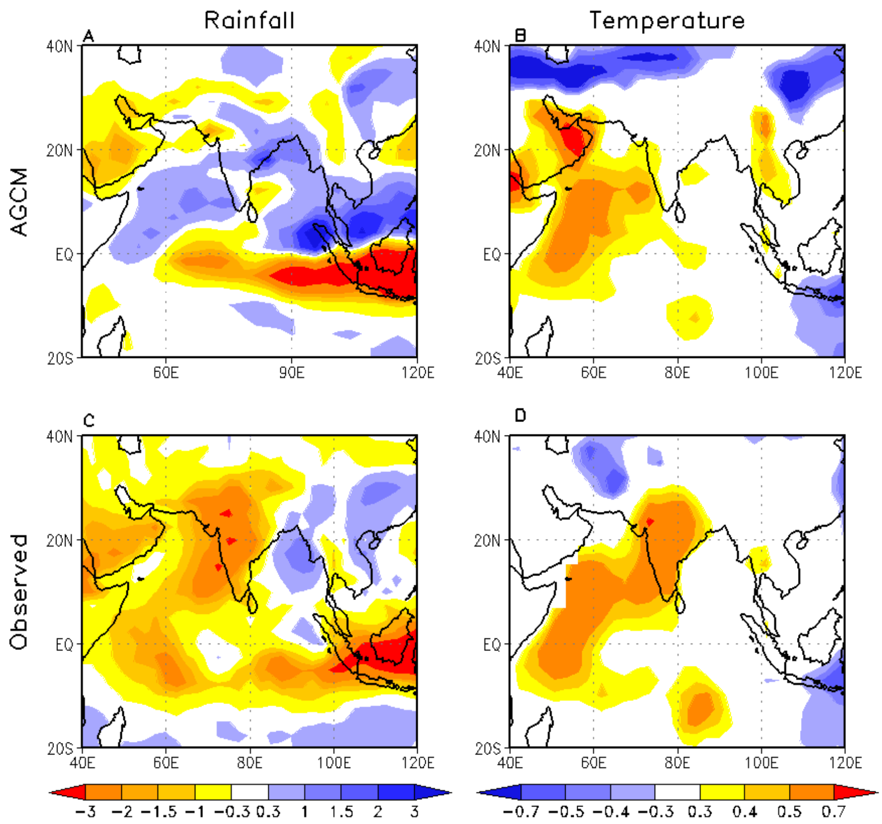

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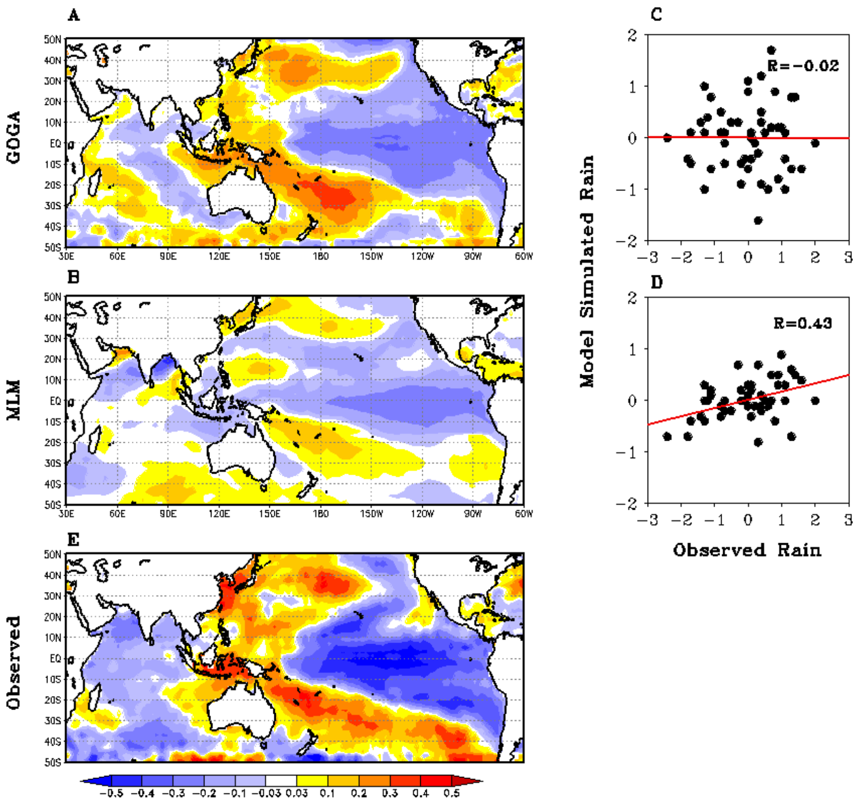

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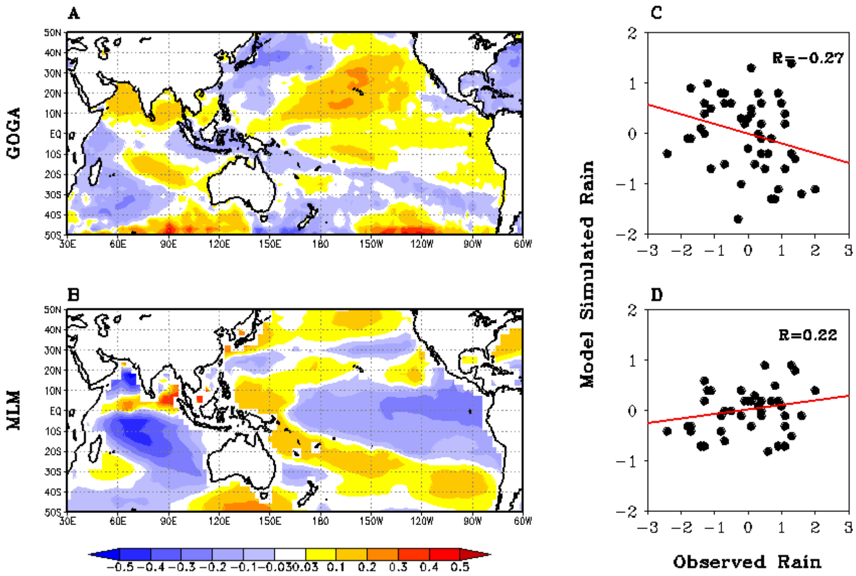

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