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Advancing dynamical prediction of Indian monsoon rainfall

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[1] Despite advances in seasonal climate forecasting using dynamical models, skill in predicting the Indian monsoon by such methods has proven poor. Our analysis identifies a flaw in the hitherto popular design of prediction systems in which atmospheric models are driven with a projected ocean surface temperature. Such a configuration presupposes Indian monsoon variability to be a consequence solely of the atmosphere reacting to the ocean. It is becoming increasingly evident that the Indian monsoon is suitably described as a fully coupled ocean-land-atmospheric system, though implications for skill have not been demonstrated. We discover significant improvements in the skill of Indian monsoon predictions when atmospheric models are not constrained by specified observed SSTs in the Indian Ocean warm pool region. Evidence comes from intercomparing 50-years of monsoon skill in atmospheric models using specified SSTs with skill in coupled ocean atmosphere models. **Citation:** Krishna Kumar, K., M. Hoerling, and B. Rajagopalan (2005), Advancing dynamical prediction of Indian monsoon rainfall, *Geophys. Res. Lett.*, *32*, L08704, doi:10.1029/2004GL021979.

[2] 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; *Krishna Kumar et al.*, 1995; *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 [*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 calculated Indian summer monsoon rainfall predictability in 10 different AGCMs 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). (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 ~300 km horizontal resolution.) Ensemble methods are used in which individual runs differ by their atmospheric initial conditions, but employ identical observed SSTs as lower boundary forcing. A 'perfect model' skill is measured by the 50-year averaged correlation between June–September Indian monsoon rainfall occurring in one model realization with that occurring in the mean of the remaining runs of the same model. (Monsoon rainfall from the models is the total rainfall over 8–30N and 70–90E.) The results for all models are summarized by plotting the probability density function (PDF) of correlations.

[3] As shown in Figure 1 (red curve), a 0.65 median correlation indicates that over 40% of the year-to-year Indian monsoon rainfall variations are oceanic controlled [*Goswami*, 1998; *Kang et al.*, 2004], arguing for a high predictability within this 'perfect model' scenario. Such high correlation skill indicates the AGCMs' 50-year Indian summer monsoon rainfall time history is quite reproducible from one integration to another, with prospects for predictive skill to the extent SSTs could themselves be accurately forecast. It should be noted that predictability is bounded, with 60% of the simulated Indian monsoon rainfall variance unexplained by such boundary conditions, but originating from internal atmospheric dynamics that are highly sensitive to the precise configuration of atmospheric initial conditions.

[4] However, the actual simulation skill of Indian monsoon rainfall is much lower than the 'perfect model' estimate. The 1950–1999 temporal correlation between each of our 10 models' ensemble mean Indian monsoon rainfall and observations [*Parthasarathy et al.*, 1994] is computed, and is again summarized with a PDF (Figure 1, blue curve). 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]. 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.

[5] Why are these theoretical 'perfect model' skill scores not being achieved? One possibility is that, compared to the GCMs, the observed year-to-year Indian monsoon rainfall is much more determined by internal atmospheric dynamics, rather than by the year-to-year swings of an SST-forced boundary signal. We found that this internal atmospheric source of variability is not materially different between nature and models (not shown). Instead, there is a large difference in SST-forced signals, one clue for which comes from comparison of AGCM (Figure 2 (top)) and observed (Figure 2 (bottom)) monsoon season rainfall and surface

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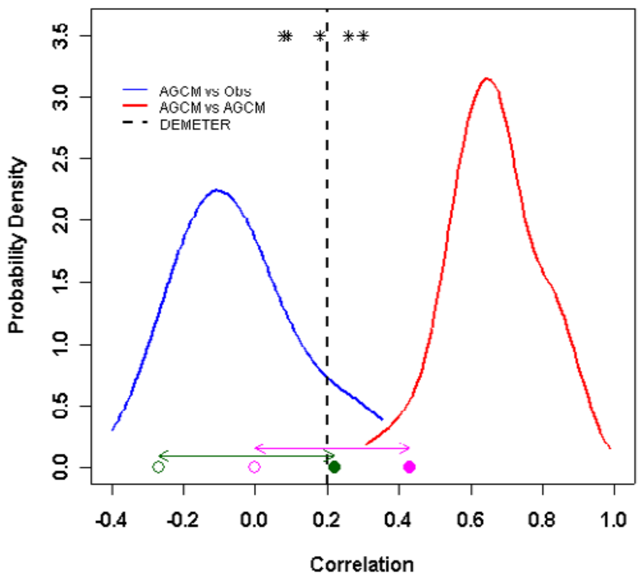

Figure 1. PDFs of correlation skill of June–September Indian monsoon rainfall based on a theoretical 'perfect model' analysis (red curve), and based on the actual skill compared to observed all Indian monsoon rain (blue curve). Analysis is based on 10 AGCMs forced with observed global SSTs of 1950–1999. Closed coloured 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. Stars indicate the spread of Indian monsoon rainfall correlation skill of the 7 coupled model hindcasts from DEMETER and the black dashed line is their median skill.

temperature anomalies during El Niño/Southern Oscillation (ENSO). In observations, much of India suffers drought during ENSO's warm phase (bottom left) and anomalously warm surface temperatures coincide with this drying over the sub-continent and adjacent sea (bottom right). These are conditions known to result from the atmospheric feedback by anomalous winds that act to suppress rainfall [*Klein et al.*, 1999; *Alexander et al.*, 2002]. In the simulations of one model (NCAR CCM3), Indian drought is not produced and there is a large-scale increase in rainfall over the warmest SSTs of the Indian Ocean and Arabian Sea (top left). The particular model chosen may be an extreme example in so far as it exhibited lowest simulation skill among the 10. However, we found that more than half of the 10 models fail to generate monsoon drought during El Niño (not shown). Another clue comes from the fact that nearly all models have a positive correlation between their Indian monsoon rainfall and area-averaged Indian Ocean SSTs, contrary to the strong negative correlation observed. We postulate that such misrepresentation of air-sea energy exchange, also identified in other studies [e.g., *Clemens and Oglesby*, 1992; *Kumar and Hoerling*, 1998; *Wang et al.*, 2003, 2004; B. Wang et al., Fundamental challenges in prediction of summer monsoon rainfall, submitted to *Geophysical Research Letters*, 2005, to be a major cause for degraded skill.

[6] 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

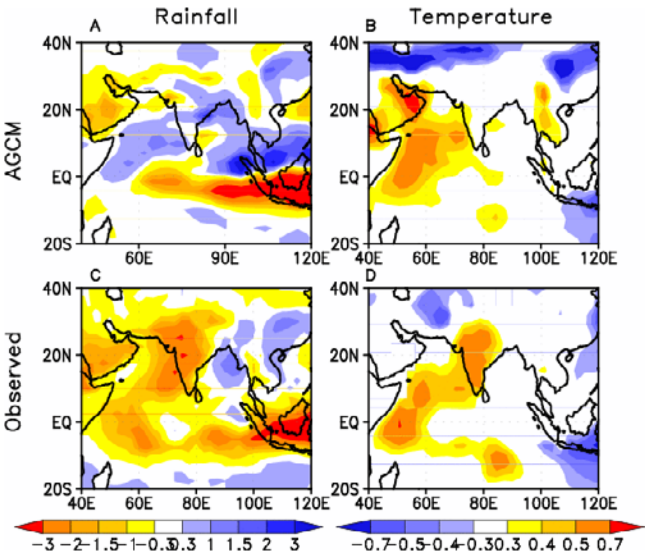

Figure 2. Monsoon season warm minus cold ENSO climate signals of, (a) ensemble mean rainfall (mm/day) from NCAR/CCM3 AGCM, (b) same as A but for surface temperatures (°C), (c) same as A but for satellite estimated rainfall derived from outgoing long-wave radiation (OLR) (d) same as B but for observed temperature. Note that SSTs have been prescribed in the AGCM. Period of analysis is 1950–1999, except 1975–2002 for OLR.

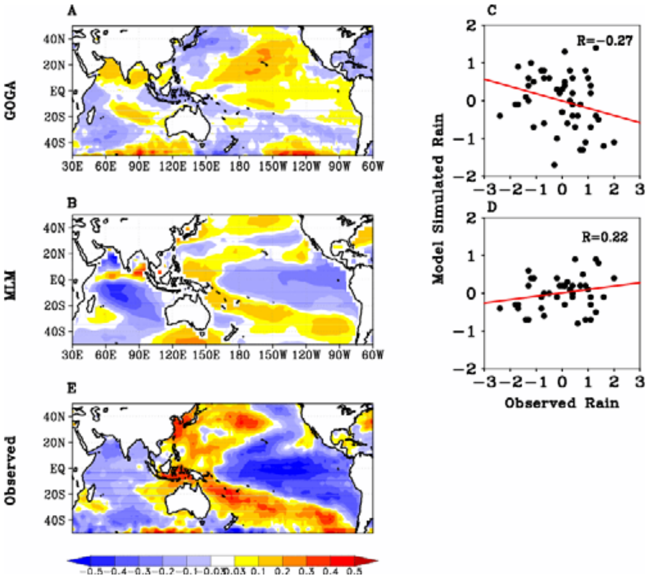

Figure 3. Correlation maps of (a) observed SSTs and monsoon rainfall simulated from uncoupled NCAR-CCM3 (GOGA) model, (b) simulated SSTs and monsoon rainfall from the coupled (MLM) model. Scatter plots of standardized anomalies of observed and simulated monsoon rainfall for each year during 1950–1994 from GOGA and MLM are shown in (c) and (d), respectively. Correlation map of (e) observed SSTs and observed monsoon rainfall. Note that in the coupled model, SSTs have been prescribed between 15°N–15°S and 172°E–80°W. Correlations are for the monsoon (JJAS) season.

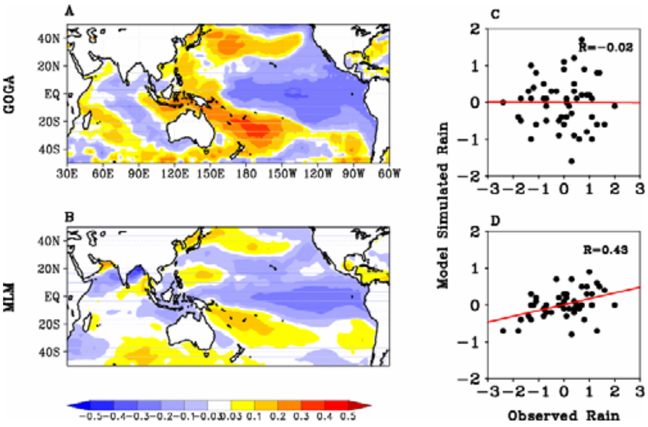

Figure 4. Correlation maps of (a) observed SSTs and monsoon rainfall simulated from uncoupled GFDLR30 (GOGA) model, (b) simulated SSTs and monsoon rainfall from the coupled (MLM) model. Scatter plots of standardized anomalies of observed and simulated monsoon rainfall for each year during 1950–1999 from GOGA and MLM are shown in (c) ad (d), respectively.

are not represented in atmospheric GCMs wherein the two-tiered design presupposes Indian monsoon variations to be described as a purely forcing-response system. Also at issue in the uncoupled approach is the inconsistency between atmospheric models and the specified observed SSTs.

[7] In a companion set of experiments using the same AGCM as in Figure 2, 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). A total of 12 simulations, each retaining identical ENSO variations [*Giannini et al.*, 2004] were analyzed. The scatter diagrams (Figure 3 (right)) reveal a dramatic change in skill, from −0.27 in the uncoupled model to +0.22 in the coupled model (also indicated in Figure 1 by the dark green circles and arrow). This is associated with a tropic-wide reversal in the Indian monsoon-SST relationship (Figure 3 (left)). 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 (Figure 3a). This correlation structure is rectified by introducing coupling (Figure 3b). Note also the substantial change in monsoon rainfall-Indian Ocean SST correlation, with the coupled model now yielding the strong inverse correlation that is seen in nature (Figure 3e).

[8] We are further able to confirm the robustness of these findings with a second set of identically designed coupled experiments (16 runs), except using a different AGCM (GFDL R30) [*Lau and Nath*, 2003]. The scatter diagrams of Figure 4 (right) compare the 50 years (1950–1999) 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 simlations, and the skill increases to +0.43, exceeding those of each of the 10 AGCMs (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.)

[9] A common feature of the coupled models is that they dramatically increase skill relative to their uncoupled counterparts (the improvement in skills are statistically significant at 95% confidence level) - a result that appears intimately tied to improvements in the correlation between the Indian monsoon rainfall and warm pool SSTs. Note in Figure 4b, as in Figure 3, the strong negative correlation between monsoon rainfall and SSTs in the cross-equatorial flow region occurring in the coupled runs. A difference between these two coupled models concerns the change in ENSO-monsoon correlation relative to their uncoupled counterparts, with there being no alteration in the GFDL set relative to the CCM set, despite comparable skill enhancements in both coupled models. This contrast demonstrates that the realism of ENSO-monsoon relations alone are insufficient for realizing predictive skill.

[10] We would add that simply removing the specified observed SSTs over the warm pool can alone improve skill. Additional GFDL simulations (8 runs) in which climatological SSTs are used everywhere outside of the tropical East Pacific rather than a mixed layer model [*Lau and Nath*, 2003] showed an improvement of Indian monsoon rainfall correlation skill from −0.02 in GOGA to +0.25. Suggested hereby is that the consistency between a GCM and the underlying SST is important for eliciting proper monsoon sensitivity.

[11] Implied in this hierarchy of model simulation studies is that fully coupled model hindcasts of Indian monsoon rainfall should exceed GOGA simulation skills. We have confirmed this to be true through an analysis of the 1-month lead hindcasts of June–September Indian Monsoon rainfall from 7 different coupled models performed for 1959–2001 as part of the DEMETER program [*Palmer et al.*, 2004]. The skill of each model is plotted in the upper portion of Figure 1, and the median skill of +0.2 is shown as a vertical black line. The hindcast skill of Indian monsoon rain exceeds the GOGA simulation skill, and this occurs despite the fact that the DEMETER runs are predicting the SSTs (which are thereby inferior to the actual observed SSTs available to GOGA runs), and that the coupled models have climate drift in their mean SSTs (which is not a limitation in the GOGA runs).

[12] What we believe coupling to achieve is that it removes the misrepresentation of air-sea interactions over the warm poool regions of the Indo-West Pacific Ocean that occurs in two-tiered systems. It is known that warm SST states of the Indian Ocean, Arabian Sea, and Bay of Bengal are typically associated with reduced cloud cover on interannual time scales in summer, yet such observed SST anomalies prescribed in AGCMs tend to excite increased cloud cover and convection that encompass the adjacent continent [*Clemens and Oglesby*, 1992]. In this regard, we found each of the AGCM's Indian monsoon rainfall to be

positively correlated with the Indian Ocean SSTs, opposite to observations. Implied is a spurious evaporative source of water vapor over the oceans that can yield erroneous moisture sources for downstream monsoon rains in the two-tiered design using observed SSTs. We noted that simply removing the specification of observed SST anomalies over this sensitive region improves skill.

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