

Prediction of the Indian summer monsoon rainfall using a state-of-the-art coupled ocean–atmosphere model

S. Janakiraman¹, Mohit Ved¹, Ramesh Naidu Laveti¹, Priyanka Yadav² and Sulochana Gadgil^{2,*}

¹Centre for Development of Advanced Computing (CDAC), CDAC Knowledge Park, No. 1, Old Madras Road, Bangalore 560 038, India

²Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore 560 012, India

A state-of-the-art model of the coupled ocean–atmosphere system, the climate forecast system (CFS), from the National Centres for Environmental Prediction (NCEP), USA, has been ported onto the PARAM Padma parallel computing system at the Centre for Development of Advanced Computing (CDAC), Bangalore and retrospective predictions for the summer monsoon (June–September) season of 2009 have been generated, using five initial conditions for the atmosphere and one initial condition for the ocean for May 2009. Whereas a large deficit in the Indian summer monsoon rainfall (ISMR; June–September) was experienced over the Indian region (with the all-India rainfall deficit by 22% of the average), the ensemble average prediction was for above-average rainfall during the summer monsoon. The retrospective predictions of ISMR with CFS from NCEP for 1981–2008 have been analysed. The retrospective predictions from NCEP for the summer monsoon of 1994 and that from CDAC for 2009 have been compared with the simulations for each of the seasons with the stand-alone atmospheric component of the model, the global forecast system (GFS), and observations. It has been shown that the simulation with GFS for 2009 showed deficit rainfall as observed. The large error in the prediction for the monsoon of 2009 can be attributed to a positive Indian Ocean Dipole event seen in the prediction from July onwards, which was not present in the observations. This suggests that the error could be reduced with improvement of the ocean model over the equatorial Indian Ocean.

Keywords: Ocean–atmosphere model, prediction, rainfall, summer monsoon.

OUR experience of the severe drought in 2009 has once again brought to the fore the poor skill of the dynamical models of the atmosphere and the coupled atmosphere–ocean system, in generating forecasts of the Indian summer monsoon rainfall (ISMR). As for the droughts of 2002 and 2004 (ref. 1), the vast majority of such models at various international centres did not even predict a

deficit in ISMR in 2009, leave alone a drought of the severity experienced². Yet, prediction of ISMR and particularly for the occurrence/non-occurrence of the extremes (i.e. droughts (excess) rainfall seasons defined as seasons with ISMR deficit (excess) of 10% or more from the average rainfall) continues to be extremely important in view of the large impact on agriculture and GDP³. Clearly, concerted efforts are needed to improve the models used for generating such predictions. The Ministry of Earth Sciences, Government of India has proposed a National Monsoon Mission (<http://dod.nic.in>) to achieve this in a time-bound manner.

An important focus of research in the mission is the prediction of ISMR by a state-of-the-art model of the National Centres for Environmental Prediction (NCEP), USA. The climate forecast system (CFS), the fully coupled ocean–land–atmosphere dynamical seasonal prediction system, which became operational at NCEP in August 2004, provides important advances in operational seasonal prediction on a number of fronts⁴. The atmospheric component of CFS is a lower-resolution version of the global forecast system (GFS) that was the operational global weather prediction model at NCEP during 2003. The ocean component is the modular ocean model version 3 (MOM3) of the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, USA. The atmospheric and oceanic components are coupled with no flux adjustment or correction. The two components exchange daily-averaged quantities such as heat and momentum fluxes, once a day. Because of the difference in latitudinal domain, full interaction between atmospheric and oceanic components is confined to 65°S–50°N. Poleward of 74°S and 64°N, the sea surface temperature (SST) data needed for the atmospheric model are taken from observed climatology. Between 74°S and 65°S, and between 64°N and 50°N, SSTs for the atmospheric component are a weighted average of the observed climatology and SST from the ocean component of CFS. The weights vary linearly with latitude such that SSTs at 74°S and 64°N equal the observed climatology and SSTs from 65°S and 50°N equal values from the ocean component. Sea-ice extent is prescribed from the observed climatology.

*For correspondence. (e-mail: sulo@caos.iisc.ernet.in)

The CFS model has been ported on the PARAM Padma, a high-performance parallel computing system developed at the Centre for Development of Advanced Computing (CDAC), Bangalore. A set of retrospective predictions for the summer monsoon (June–September) season of 2009 have been generated, using five initial conditions for the atmosphere and one initial condition for the ocean for May 2009. Whereas a large deficit in the summer monsoon rainfall was experienced over the Indian region (with the all-India rainfall deficit by 22% of the long-period average), the ensemble average prediction was for above-average rainfall during the summer monsoon. In order to improve the model to yield better predictions of the monsoon rainfall, it is important to understand factors that lead to such errors.

At NCEP, nine-month long retrospective predictions have been made from 1981 onwards with 15 ensemble members starting from different initial conditions⁴. This rich dataset, which makes possible systematic study of the skill of the CFS model in the prediction of any phenomenon such as El Niño or ISMR, has been generously made available to the scientific community via the NCEP website (<http://cfs.ncep.noaa.gov/menu/download/>). Prediction of the Asian/Indian summer monsoon by CFS has been assessed by analysis of these retrospective forecasts^{5–9}. Yang *et al.*⁵ showed that the model successfully simulates many major features of the Asian summer monsoon, including the climatology and interannual variability of major precipitation centres and atmospheric circulation systems. Pattanaik and Arun Kumar⁶ have shown that the anomaly correlation coefficient between the forecast rainfall anomaly and the observed rainfall anomaly over the Indian region and surrounding oceans is high for some years (e.g. 1991, 1994, 1997, 1998) and is poor for others (1982, 1984, 1987 and 1989). The correlation between rainfall over the Indian land region predicted with March–May initial conditions and that observed is shown to be significant at 95% level only for the April conditions⁹. Drbohlav and Krishnamurthy⁷ have elucidated the nature of the systematic errors and errors in interannual variability in the retrospective forecasts. Achuthavarier and Krishnamurthy⁸ have analysed long simulations of the CFS-coupled model with two different horizontal resolutions and of the one atmospheric component of CFS, viz. the GFS model. They have shown that the variability of the rainfall is overestimated in the models, especially in the uncoupled version. The coupled simulations produce more realistic precipitation and circulation patterns, whereas the improvement in the mean and variability due to higher horizontal resolution is marginal. They found that the relation between intraseasonal and interannual variation was well simulated by the CFS model.

In this article we present retrospective predictions generated at CDAC with the coupled version of CFS for the monsoon season of 2009 and simulations with the atmospheric version of CFS, viz. GFS, forced with obser-

ved SST for the seasons of 2009 and 1994. With an analysis of these runs of CFS and GFS and of some of the retrospective forecasts at NCEP, we suggest why above-average rainfall was predicted instead of the deficit rainfall that was observed for the season of 2009, and hence the possible approach to improving the predictions of ISMR. When this article was submitted to the journal, the retrospective predictions generated at NCEP for 2009 were not available. At the time of revision, they became available and hence we have included their prediction of ISMR, which is found to be consistent with that generated at CDAC. A detailed comparison of the CDAC and NCEP runs for the same initial conditions is being done and will be reported in a subsequent paper.

Data and methodology

Retrospective predictions for 2009 have been generated by the CFS model ported on the PARAM Padma computing system at CDAC, using five initial conditions for the atmosphere for 9–13 May and one oceanic initial condition for 6 May. The data for these initial conditions from NCEP were provided to us by Indian Institute of Tropical Meteorology (IITM), Pune. The same initial conditions for the atmosphere were used for the GFS simulations, which were forced by the observed SST¹⁰ for 2009. For 1994, initial conditions for the atmosphere were obtained from NCEP. The climatology for GFS⁸ is based on an AMIP (Atmospheric Model Intercomparison Project) run at NCEP. We have analysed the retrospective predictions for 1981–2008 based on April initial conditions provided by NCEP⁴. We present here only the results of the ensemble averages of the predictions and simulations. Rainfall data for the tropical belt from GPCP¹¹, for the Indian region from Parthasarathy *et al.*¹² (which is updated and available at <http://www.tropmet.res.in>) and SST data from Reynolds *et al.*¹⁰ have been used for comparison with the predictions and simulations.

Prediction with the coupled version of CFS

The mean June–September rainfall pattern from the retrospective predictions for 1981–2008 and from the AMIP run of GFS, is realistic with all the major rain-belts being well simulated⁵ (Figure 1). However, rainfall is less than that observed over the Indian monsoon zone north of 20°N (ref. 8). It is in excess of that observed over the northeastern part of India, Arabian Sea, east coast of the Bay of Bengal, most of the equatorial Indian Ocean and over the equatorial Pacific⁸.

For 1981–2009, the variation of the ISMR anomaly predicted by the coupled version of CFS and the observed anomaly is depicted in Figure 2. The retrospective prediction from CDAC for 2009 is also shown. Note that the observed normalized anomaly of ISMR is based on the mean and standard deviation of 1981 onwards, since the model results are available only for that period.

Although the correlation between the predicted and observed ISMR is only 0.22, i.e. rather poor (as pointed out by Pattanaik *et al.*⁹ and suggested in earlier studies), it is interesting that for most of the years (20 out of 28), the predicted anomaly is of the same sign as that observed. Furthermore, out of the eight points with the predicted anomaly of the opposite sign to that observed, the magnitude of the predicted anomaly is not large for five points. The major outliers, in the wrong quadrants, are the severe drought of 2009, the excess monsoon season of 1983 and the deficit monsoon of 2000. If these three outliers are omitted, the correlation (coefficient 0.64) is highly significant. An important feature is the prediction of a positive anomaly of ISMR with magnitude close to one standard deviation for the excess monsoon season of 1994, for which most of the Atmospheric General Circulation Models (AGCMs) simulate a deficit ISMR even when forced with the observed SST^{1,13}. The error in prediction of the normal monsoon season of 1997, which could also not be simulated by most of the AGCMs¹⁴, is not very large. However, the error in prediction of the severe drought of 2002 is rather large.

Some insight into why major errors occur in the prediction by CFS can be gained from what is known^{1,13,15} about the links of the interannual variation of the monsoon with the important modes, El Niño and Southern Oscillation (ENSO) and Equatorial Indian Ocean Oscilla-

tion (EQUINOO). For depicting the link with ENSO we define an ENSO index as the negative of the normalized SST anomaly for Niño 3.4, so that positive values (cold phase) are favourable for the monsoon. Suppression of convection/rainfall over the eastern part of the equatorial Indian Ocean (90°–110°E, 0°–10°S; henceforth EEIO) and enhancement over the western part (50°–70°E, 10°S–10°N; henceforth WEIO) are characteristics of the positive phase of EQUINOO, which is favourable for monsoon rainfall over the Indian region¹⁶. The negative phase of EQUINOO is associated with convection/rainfall anomalies of opposite sign, i.e. enhancement over EEIO and suppression over WEIO. EQWIN, the index used for EQUINOO, is the negative of the anomaly of the zonal component of the surface wind at the equator (60°–90°E, 2.5°S–2.5°N). It is highly correlated (coefficient 0.81) with the difference between the outgoing longwave radiation (OLR) of WEIO and EEIO. Gadgil *et al.*¹⁶ have shown that every drought (excess monsoon season) during 1958–2003 is associated with an unfavourable (favourable) phase of either ENSO or EQUINOO, or both. Thus, there is a strong relationship between extremes of ISMR and ENSO index and EQWIN. This relationship is also found to be valid for the subsequent droughts of 2004 and 2009 (ref. 17). Using data for 1881–1998, Ihara *et al.*¹⁸ have shown that the linear reconstruction of ISMR on the basis of a multiple regression from an ENSO index and EQWIN better specifies ISMR, than regression with only the ENSO index.

Positive (negative) phases of the Indian Ocean dipole (IOD) mode are characterized by negative (positive) SST anomalies of EEIO and positive (negative) SST anomalies of WEIO. The index for IOD, DMI, is based on the difference between the SST anomalies of EEIO and WEIO. EQUINOO has been considered to be the atmospheric component of the coupled IOD mode and strong positive IOD events such as 1994 and 1997 are associated with strong positive phases of EQUINOO. However, positive and negative phases of EQUINOO do not have a one-to-one relationship with positive and negative IOD events. Thus the correlation between EQWIN and DMI for the summer monsoon season is only 0.52. On the other hand, the atmospheric and oceanic components of ENSO are tightly coupled with a high correlation between the southern oscillation index and the different El Niño indices (e.g. correlation coefficient of 0.86 for the Niño 3.4 index). Saji *et al.*¹⁹ had shown that while DMI is highly correlated with rainfall over eastern Africa and western equatorial Indian Ocean, correlation with the rainfall over the Indian region is poor. Ihara *et al.*¹⁸ also found that in contrast to EQWIN, no skill is added to the specification of ISMR by the DMI index when analysed over the long interval from 1881 to 1998. Thus while the link between ISMR and EQUINOO has been clearly demonstrated, the association between IOD and ISMR is only seen when there is a strong positive IOD event which is characterized by a strong positive EQUINOO.

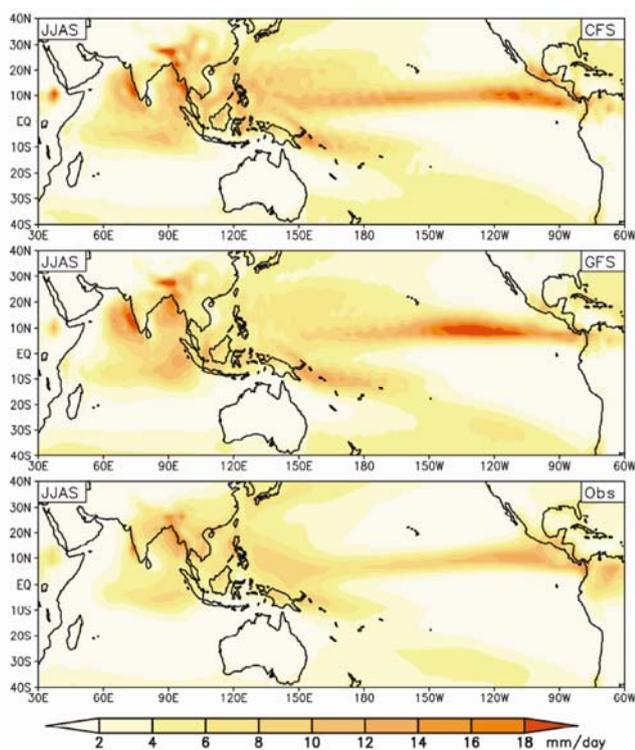


Figure 1. Mean June–September rainfall from the retrospective predictions of CFS for 1981–2008 (top); AMIP run of GFS for 1961–2002 (middle) and GPCP dataset for 1979–2009 (bottom).

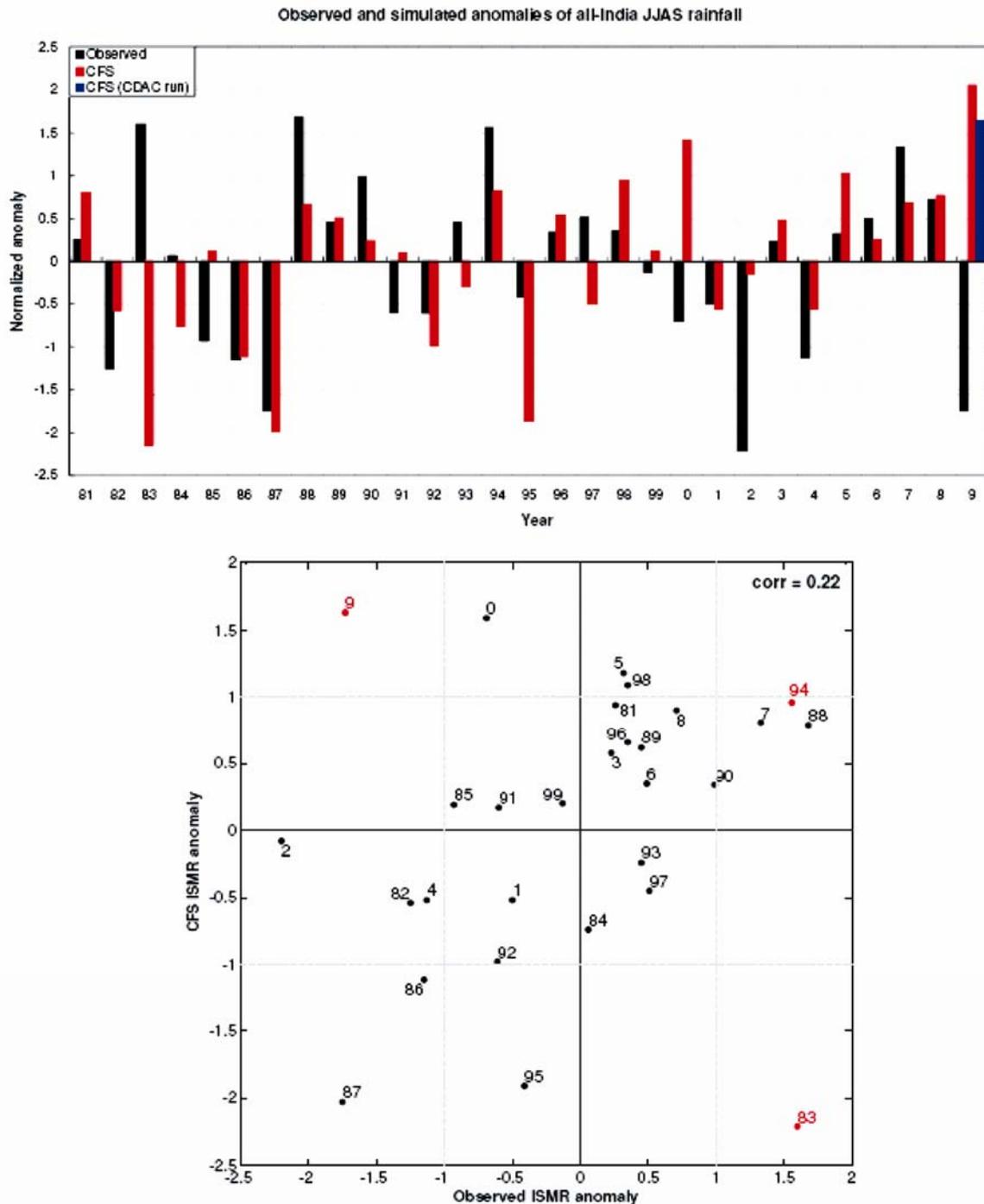


Figure 2. Variation of the observed ISMR and retrospective prediction of ISMR of CFS from NCEP for 1981–2008, from CDAC for 2009 with years (top). Predicted versus observed ISMR for 1981–2009 (bottom).

The variation of the observed and simulated ISMR with this ENSO index is shown in Figure 3. It is seen that in 1994, although the ENSO was unfavourable, excess monsoon occurred. In fact, the season of 1994 was characterized by a highly favourable phase of EQUINOO¹. The excess monsoon season of 1983 is somewhat complex with the June and July rainfall being deficit and excess in

August and September, leading to a large excess for the seasonal rainfall. Although ENSO was highly unfavourable in June, it became favourable in August and more so in September, whereas EQUINOO was favourable throughout and particularly so in September. The severe drought of 2009 was associated with unfavourable phases of both the modes (as in the case of the severe drought of

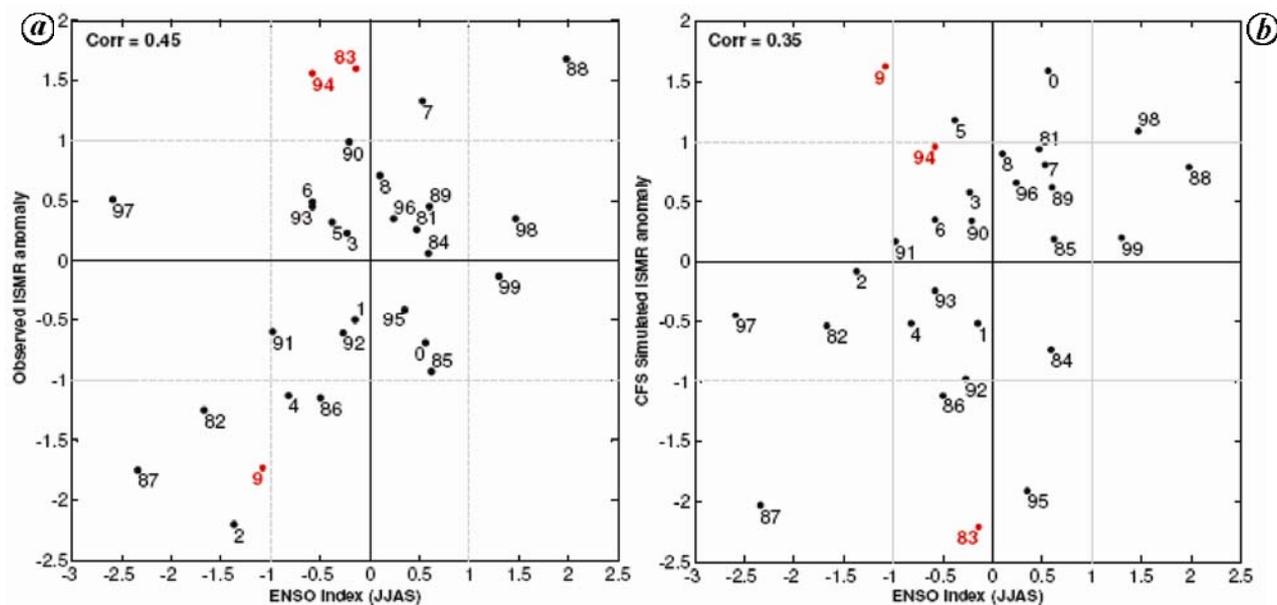


Figure 3. Observed ISMR versus observed ENSO index (*a*) and predicted ISMR versus observed ENSO index (*b*) for 1981–2009.

2002), with an additional unfavourable factor (reversal of the SST gradient between the equatorial Indian Ocean and the Bay of Bengal to its north) playing a role in the large deficit in June 2009 (refs 17, 20). We focus here on the seasons of 2009 and 1994.

The monsoon seasons of 1994 and 2009

For the rainfall in June–September 1994, the anomaly predicted by CFS, with GFS (forced by observed SST) and the observed anomaly are shown in Figure 4*a*. As expected from the results of the international AMIP¹ and the national intercomparison project, Seasonal Prediction of the Indian Monsoon (SPIM)¹³, the ISMR anomalies are negative in the GFS simulation, despite a reasonable simulation of a positive EQUINOO manifested as positive rainfall anomalies over WEIO and negative anomalies over EEIO. On the other hand, the CFS prediction for the Indian region is close to observations with the positive anomalies over WEIO linking with those over the Indian region. The positive EQUINOO is stronger than that observed in the CFS prediction. The observed and predicted SST anomaly is shown in Figure 4*b*, along with the difference in the predicted and observed SST fields. It is seen that the SST anomalies characterizing the strong positive IOD event are stronger than those observed in the prediction. Furthermore, the predicted SST anomaly is negative over 0°–10°S of the central and eastern Pacific, and the SST over this region is markedly cooler than that observed. Thus instead of the observed weak El Niño, a weak cool phase is predicted. The predicted excess monsoon rainfall over the Indian region in 1994 is,

therefore, associated with a stronger than observed positive IOD and EQUINOO, and a favourable ENSO.

Variation of the rainfall and SST anomalies during the summer monsoon of 2009 was more complex^{17,20}. The observed June–September rainfall was deficit over a large part of the Indian region; it was also deficit in the GFS simulation, but the rainfall anomaly predicted by CFS was positive over a large part of the country (Figure 5*a*). Whereas the El Niño signature is seen over the Pacific in the observed as well as predicted/simulated patterns, there are marked differences between the prediction/simulation and observations over the equatorial Indian Ocean. A prominent feature of the CFS prediction is a strong positive EQUINOO phase, which is rather weak in the GFS prediction and hardly seen in the observations.

The monthly rainfall anomaly patterns from the observations and the retrospective predictions/simulation with CFS and GFS are shown in Figure 5*b*. Whereas the observed monthly all-India rainfall anomalies were negative for each month, being of very large magnitude in June and moderate in July, the predicted anomalies were high and positive for June, and positive for July and September (normalized anomalies being 2.85, 0.58 and 0.45 respectively). It is seen that for June 2009, as observed, the GFS prediction is for a deficit in rainfall over the Bay of Bengal and the Indian region; but the magnitude of the predicted deficit is larger than that observed. Also there is intensification of rainfall over EEIO of magnitude much larger than that observed. However, the rainfall anomaly pattern for the GFS prediction for July is similar to that of June and different from that observed over the Indian region as well as the equatorial Indian Ocean. The response of GFS for August and September is a stronger-

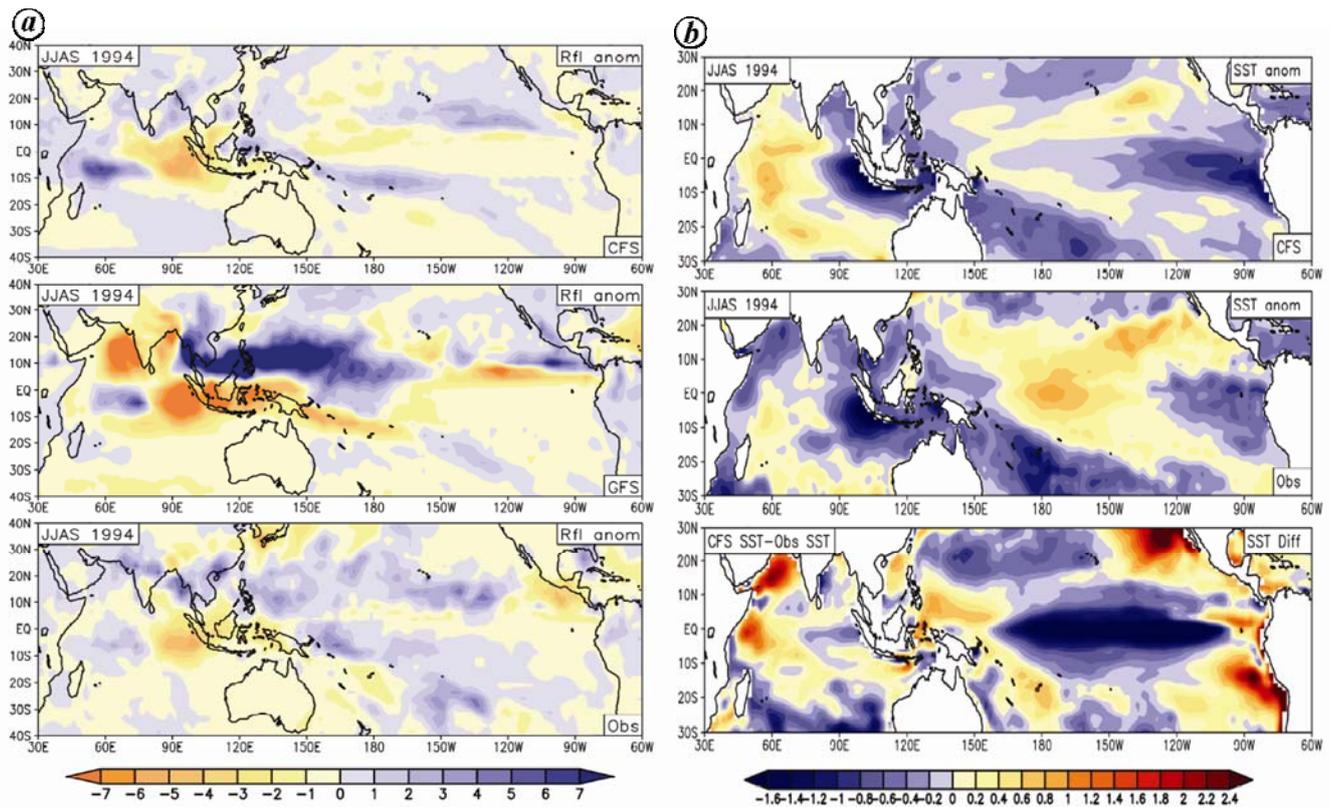


Figure 4. *a*, Anomaly of rainfall for June–September 1994 from the retrospective predictions of NCEP with CFS (top); simulation by GFS (middle) and observed (bottom). *b*, SST anomaly predicted by CFS (top) observed SST anomaly (middle) difference between predicted and observed (bottom).

than-observed El Niño and deficit rainfall over the Indian region. On the other hand, the CFS prediction for June 2009 is for a positive anomaly of rainfall over the Indian region (instead of the observed negative anomaly), with a suppression of rainfall over almost the entire equatorial Indian Ocean. However, for July 2009, the CFS prediction is not very different from that observed over the equatorial Indian Ocean as well as the Indian region. As observed¹⁷, the phase of EQUINOO is positive with suppression of rainfall over EEIO and enhancement over WEIO. In the CFS prediction, this positive phase of the EQUINOO persists in August and September, whereas in observations it became negative.

The difference between the observed and predicted CFS rainfall patterns for the different months is directly linked to the difference between the observed and predicted SST patterns (Figure 6). In June 2009, there were large negative anomalies over the Bay of Bengal and positive anomalies over EEIO and WEIO, which resulted in a reversal of the meridional SST gradient from what is generally observed¹⁷. The predicted SST anomaly over the Bay of Bengal is also negative, but less intense. A major difference between the predicted and observed SST anomaly patterns during July–September is the presence of a large negative SST anomaly over EEIO and a positive one over WEIO (i.e. positive phase of the IOD), which is not seen in the observed patterns. This was asso-

ciated with a positive phase of EQUINOO during July–September in the CFS-predicted rainfall patterns, whereas the observed positive phase of EQUINOO in July was not associated with SST anomalies of opposite sign over WEIO and EEIO.

Summary and concluding remarks

The link of the interannual variation of the Indian monsoon to ENSO with a high propensity of droughts is well known and generally AGCMs when forced with observed SST are able to simulate this link^{1,13}. However, they are not able to simulate the link with EQUINOO, which was particularly important for seasons such as 1994, which was an excess monsoon season despite a weak El Niño. Hence most AGCMs simulate a deficit ISMR in response to the unfavourable ENSO^{1,13}. An important feature of the retrospective predictions by the coupled CFS is that the sign of the ISMR anomaly is predicted for extremes associated with ENSO (such as the El Niño of 1987 and La Niña of 1988), but the positive sign of the ISMR anomaly in 1994 is also predicted. This can be attributed to the accurate prediction of the positive phases of IOD and EQUINOO, and capturing the link of the Indian monsoon to EQUINOO. Rajeevan and Nanjundiah²¹ have shown that in most of the coupled models of IPCC-AR4,

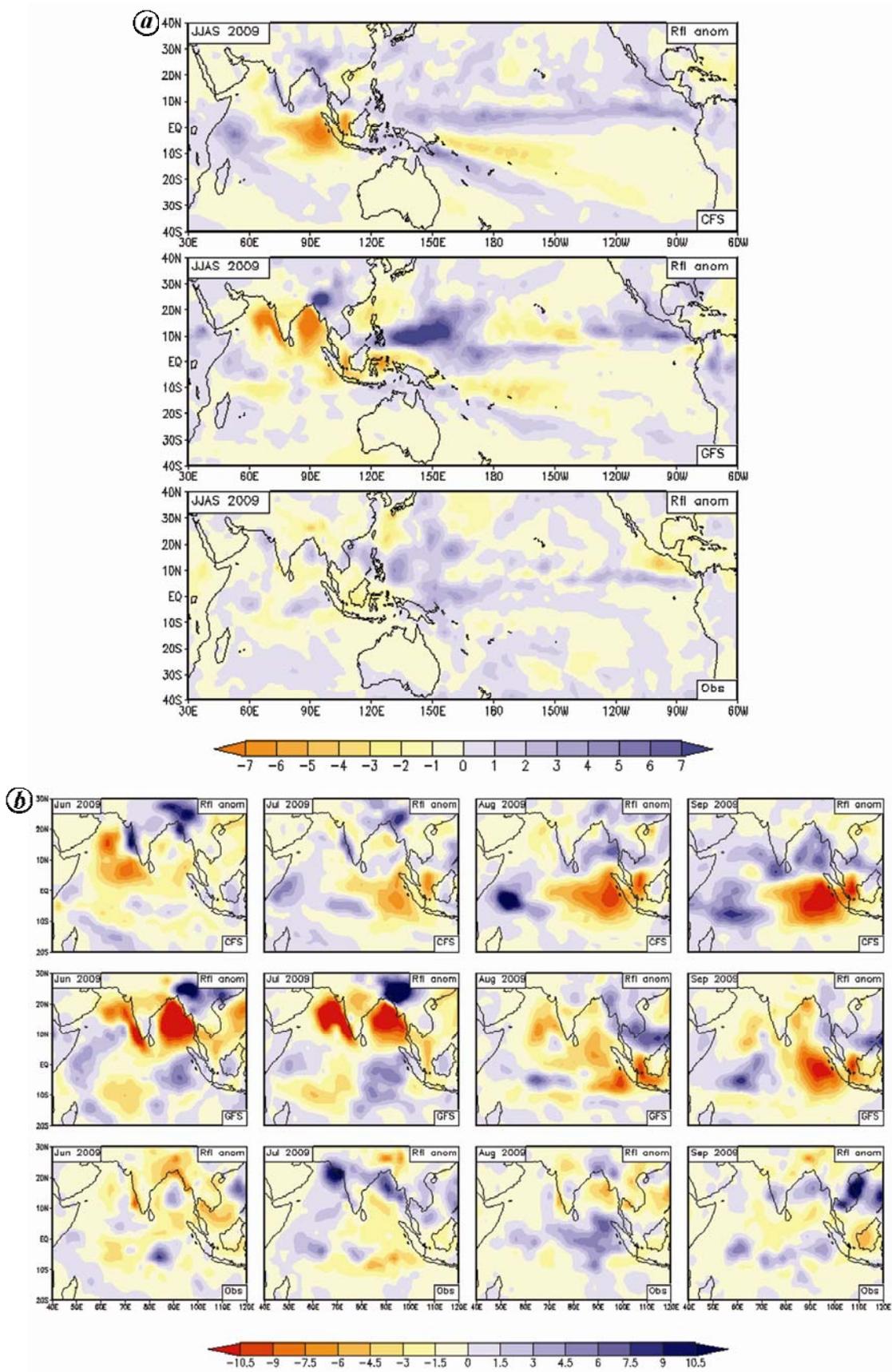


Figure 5. *a*, Anomaly of the rainfall of June–September 2009 from the retrospective predictions of CDAC with CFS (top); simulation by GFS (middle) and observed (bottom). *b*, Same as (*a*), but for individual months June–September.

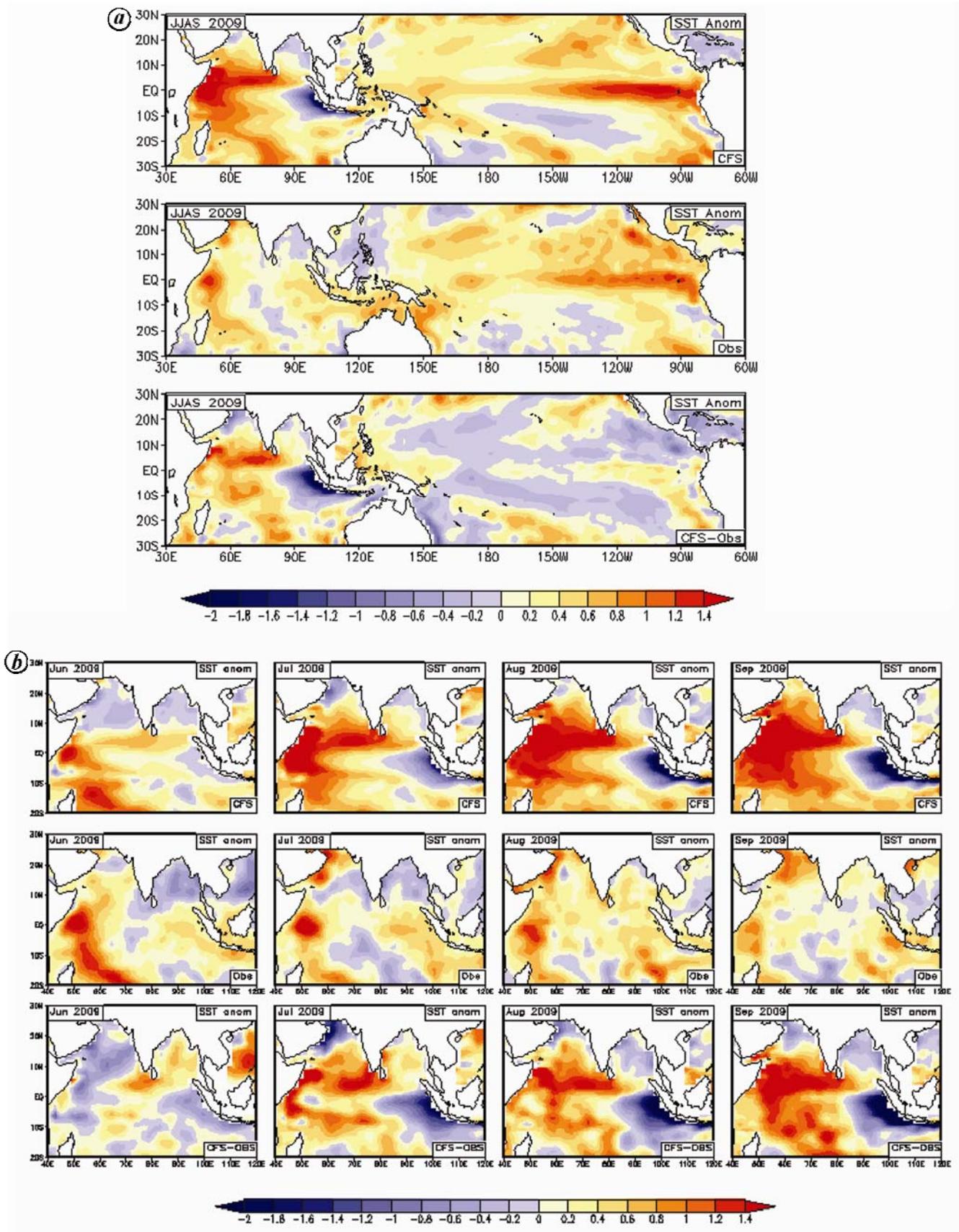


Figure 6. *a*, Anomaly of SST of June–September 2009 from the retrospective predictions of CDAC with CFS (top); and observed (middle). (Bottom) Difference between the predicted and observed SST anomaly. *b*, Same as (*a*), but for individual months June–September.

ISMR is poorly correlated with EQUINOO. Thus CFS appears to be superior to them in capturing this important link. In fact, stronger-than-observed positive phase of IOD and EQUINOO and weaker-than-observed unfavourable phase of ENSO contributed to the prediction of an ISMR extreme for 1994. However, in 2009, an unrealistic evolution of a positive IOD event has led to the large error in prediction of rainfall over the Indian region. It has been pointed out that a positive IOD is a systematic error in CFS^{5,7}. It appears that if not removed, this can lead to major errors in the prediction of ISMR. It may be noted that there was a large error in the prediction of the severe drought of 2002 as well. A negative phase of EQUINOO made a significant contribution to the deficit rainfall in 2002 (ref. 1). It is possible that the systematic error precludes a realistic simulation of negative EQUINOO/IOD as well. This suggests that in the coupled model there is excessive cooling of EEIO, which could be the manifestation of an unrealistically shallow thermocline of EEIO. Perhaps this defect could be overcome by appropriate bias correction.

Of the two major modes involved in the interannual variation of the Indian monsoon, viz. ENSO and EQUINOO, there has been remarkable progress in the understanding of ENSO in the last three decades and reasonably accurate predictions about the transitions to El Niño and La Niña have been generated. However, further work is required to understand in depth the transitions to strong positive and negative phases of IOD and EQUINOO. Different hypotheses have been proposed for triggering of positive IOD events such as El Niño²² or severe cyclones over the Bay of Bengal in April/May²³. However, which mechanism operates in nature is not clear. Given the high propensity for the genesis of positive IOD events, the CFS model could prove to be an extremely useful tool in understanding the triggering of these events and hence lead to improvement in the model for more realistic predictions of the transitions of EQUINOO, IOD and hence the Indian monsoon.

1. Gadgil, Sulochana, Rajeevan, M. and Nanjundiah, R., Monsoon prediction – why yet another failure? *Curr. Sci.*, 2005, **88**, 1389–1400.
2. Nanjundiah, R. S., A quick look into assessment of forecasts for the Indian summer monsoon rainfall in 2009. CAOS, IISc, October 2009.
3. Gadgil, Sulochana and Gadgil, Siddhartha, The Indian monsoon, GDP and agriculture. *Econ. Polit. Wkly*, 2006, **XLI**, 4887–4895.
4. Saha, S. *et al.*, The NCEP climate forecast system. *J. Climate*, 2006, **19**, 3483–3515.
5. Yang, S., Zhang, Z., Kousky, V. E., Higgins, R. W., Yoo, S. H., Liang, J. and Fan, Y., Simulations and seasonal prediction of the Asian summer monsoon in the NCEP climate forecast system. *J. Climate*, 2008, **21**, 3755–3775.
6. Pattanaik, D. R. and Arun Kumar, Prediction of summer monsoon rainfall over India using the NCEP climate forecast system. *Climate Dyn.*, 2010; doi: 10.1007/s00382-009-0648-y.
7. Drbohlav, H.-K. L. and Krishnamurthy, V., Spatial structure, forecast errors and predictability of South Asian monsoon in CFS

monthly retrospective forecasts. *J. Climate*, 2010; doi:10.1175/2010JCL12356.1

8. Achuthavarier, D. and Krishnamurthy, V., Relation between intraseasonal and interannual variability of the South Asian monsoon in the National Centers for Environmental Predictions forecast systems. *J. Geophys. Res.*, 2010, **115**, D08104.
9. Pattanaik, D. R., Arun Kumar and Tyagi, A., Development of empirical–dynamical hybrid forecasts for the Indian monsoon rainfall using the NCEP Climate Forecast System. IMD Met Monograph Synoptic Meteorology No. 11/2010, 2010.
10. Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. and Wang, W. Q., An improved *in situ* and satellite SST analysis for climate. *J. Climate*, 2002, **15**, 1609–1625.
11. Adler, R. F. *et al.*, The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeorol.*, 2003, **4**, 1147–1167.
12. Parthasarathy, B., Munot, A. A. and Kothawale, D. R., All-India monthly and seasonal rainfall series 1871–1993. *Theor. Appl. Climatol.*, 1994, **49**, 217–224.
13. Gadgil, Sulochana and Srinivasan, J., Seasonal prediction of the Indian Monsoon. *Curr. Sci.*, 2011, **100**, 343–353.
14. Wang, B., Kang, I. S. and Lee, Y. J., Ensemble simulations of Asian–Australian monsoon variability during 1997/1998 El Niño by 11 AGCMs. *J. Climate*, 2004, **17**, 803–818.
15. Gadgil, Sulochana, Rajeevan, M. and Francis, P. A., Monsoon variability: Links to major oscillations over the equatorial Pacific and Indian oceans. *Curr. Sci.*, 2007, **93**(2), 182–194.
16. Gadgil, Sulochana, Vinayachandran, P. N., Francis, P. A. and Gadgil, Siddhartha, Extremes of Indian summer monsoon rainfall, ENSO, equatorial Indian Ocean Oscillation. *Geophys. Res. Lett.*, 2004, **31**, doi: 10.1029/2004GL019733.
17. Francis, P. A. and Gadgil, Sulochana, Towards understanding the unusual Indian monsoon in 2009. *J. Earth Syst. Sci.*, 2010, **119**(4), 397–415.
18. Ihara, C., Kushnir, Y., Cane, M. A. and De la Peña, V., Indian summer monsoon rainfall and its link with ENSO and the Indian Ocean climate indices. *Int. J. Climatol.*, 2007, **27**, 179–187.
19. Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., A dipole mode in the tropical Indian Ocean. *Nature*, 1999, **401**, 360–363.
20. Francis, P. A. and Gadgil, Sulochana, The aberrant behaviour of the Indian monsoon in June 2009. *Curr. Sci.*, 2009, **97**(9), 1291–1295.
21. Rajeevan, M. and Nanjundiah, R. S., Coupled model simulations of twentieth century climate of the Indian summer monsoon. In *Platinum Jubilee Special Volume of the Indian Academy of Sciences*, Indian Academy of Sciences, Bangalore, 2009, pp. 537–568.
22. Annamalai, H. *et al.*, Coupled dynamics over the Indian Ocean: spring initiation of the zonal mode. *Deep Sea Res.*, 2003, **50**, 2305–2330.
23. Francis, P. A., Gadgil, Sulochana and Vinayachandran, P. N., Triggering of the positive Indian Ocean dipole events by severe cyclones over the Bay of Bengal. *Tellus*, 2007, **59A**, 461–475.

ACKNOWLEDGEMENTS. We acknowledge the generous support given by CDAC for this work, which also included providing the computational facility. We are grateful to Dr Suranjana Saha and Dr Wesley Ebisuzaki, NCEP, USA for critical inputs during porting at CDAC and Dr Suryachandra Rao, IITM, Pune for providing CFS initial conditions for the 2009 run. We thank Profs Ravi Nanjundiah and J. Srinivasan, CAOS, IISc, for suggestions during several discussions. We became aware of a lot of work done with CFS, from lectures by Dr V. Krishnamurthy, COLA and discussions with him and Dr Deepthi Achuthavarier, who also made available to us the GFS model climatology generated by Dr Bhaskar Jha of NCEP.

Received 6 August 2010; revised accepted 5 January 2011