

# Droughts of the Indian summer monsoon: Role of clouds over the Indian Ocean

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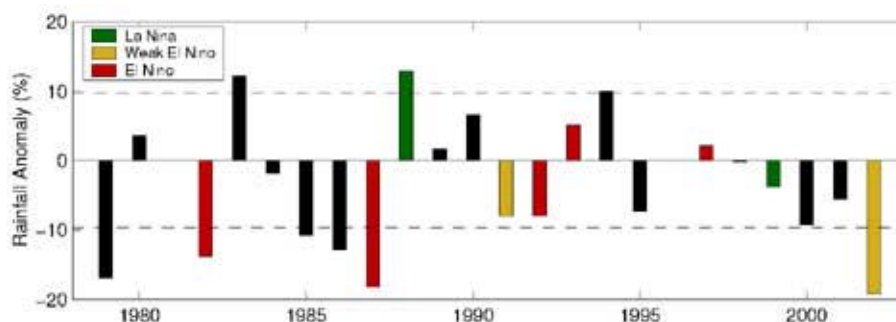
**Comparison of the evolution of the normal summer monsoon of 2003 with the unanticipated drought of 2002 led to this investigation of the role of the deep convection in the atmosphere (deep cloud systems) over the equatorial Indian Ocean. We find that the link of the Indian monsoon to events over the equatorial Indian Ocean is as important as the well-known link to the dramatic events over the Pacific (El Niño Southern Oscillation; ENSO). Over the equatorial Indian Ocean, enhancement of deep convection in the atmosphere over the western part is generally associated with suppression over the eastern part and vice versa. We call the oscillation between these two states, which is reflected in the pressure gradients and the wind along the equator, the Equatorial Indian Ocean Oscillation (EQUINOO). We show that every season with excess rainfall/drought during 1979–2002 can be ‘explained’ in terms of favourable/unfavourable phase of either this oscillation or the ENSO or both. In particular, in the monsoon season of 2002 while the ENSO phase was unfavourable but weak, the phase of the EQUINOO was highly unfavourable and a large deficit occurred in the monsoon rainfall.**

THE rainfall received over India during the four summer months from June to September is so critical for the country’s economy, that the impact of the deficit of 19% in the Indian summer monsoon rainfall in 2002 has been estimated to be well over 1% of the gross domestic production<sup>1</sup>. The monsoon of 2002 also led to considerable concern in the meteorological community, since none of the predictions for 2002 suggested a large deficit in the Indian summer monsoon rainfall. This was irrespective of whether the predictions were based on empirical models used in the country for generating operational or experimental forecasts, or generated in the different centres in the world using the atmospheric general circulation models<sup>2</sup>. After the unanticipated failure of the Indian monsoon in the summer of 2002, we observed the evolution of the monsoon of 2003 with considerable anxiety. Fortunately, the monsoon of 2003 turned out to be near normal. We present here, the insight a comparison with the monsoon of 2003 gave us into the intriguing season of 2002 and some previous droughts as well.

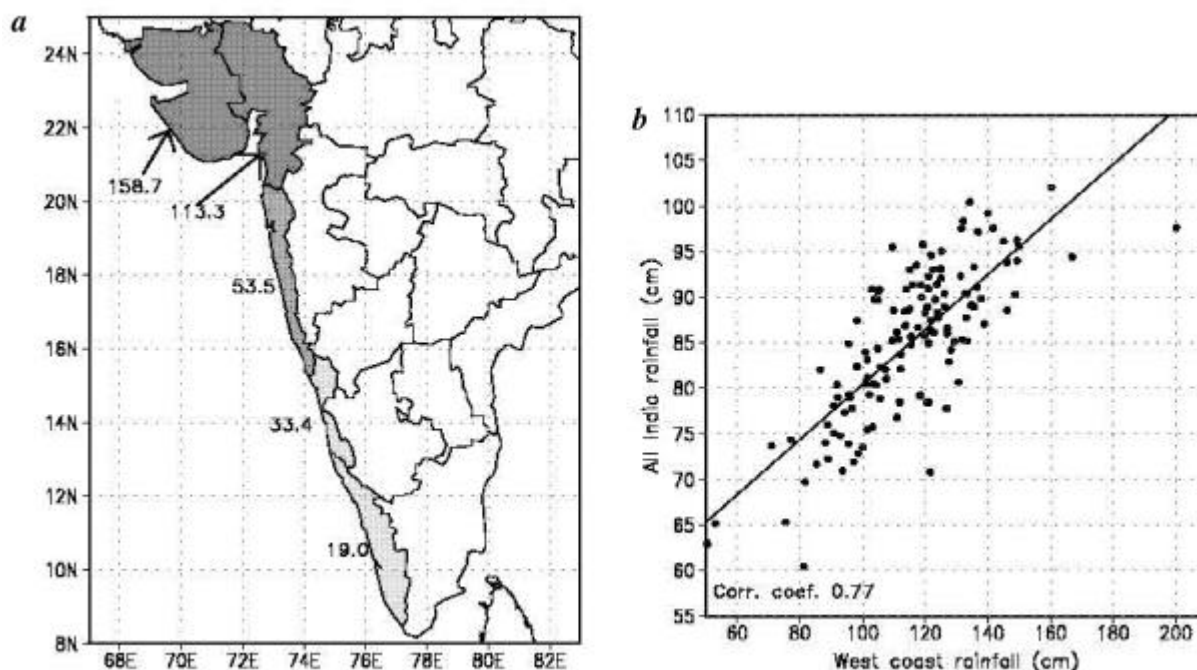
A major advance in our understanding of the year-to-year variation of the monsoon rainfall occurred in the 80s, with the discovery of a strong link with El Niño and the Southern Oscillation (ENSO), the dominant signal of interannual variation of the coupled atmosphere–ocean system over the Pacific. It was shown that there is an increased propensity of droughts during El Niño or the warm phase of this oscillation and of excess rainfall during the opposite phase, i.e. La Nina<sup>3–5</sup>. The phenomenal progress in the last two decades with the elucidation of the nature of ENSO, unravelling of the underlying mechanisms<sup>6,7</sup> and the improved capability of seasonal to interannual predictions<sup>8</sup>, was expected to lead to better predictions of the Indian monsoon. Consistent with the nature of the links of the monsoon with ENSO, the La Nina event of 1988 was associated with large excess in the All-India summer monsoon rainfall<sup>9</sup> (henceforth ISMR); and the El Niño events of 1982 and 1987 were droughts (defined as seasons with deficit in ISMR more than one standard deviation; Figure 1). However, for fourteen consecutive years beginning with 1988, there were no droughts despite the occurrence of El Niño. Further, during the strongest El Niño event of the century in 1997, the ISMR was higher than the long-term mean (Figure 1). Kumar *et al.*<sup>10</sup> suggested that the relationship between the Indian monsoon and ENSO had weakened in the recent decades. Although a weak El Niño was known to be developing in 2002, none of the predictions for 2002 suggested a large deficit in the Indian monsoon rainfall. The experience of 1997 and 2002 suggests that we do not as yet understand adequately, the response of the monsoon to El Niño.

Special features of the monsoon of 2002 were (i) the large deficit (19% of the mean) in ISMR was primarily due to an unprecedented deficit of 49% in the peak monsoon month of July and (ii) very large rainfall deficit over the west coast. An observational experiment to study the Arabian Sea Monsoon (ARMEX)<sup>11</sup> under the Indian Climate Research Programme during July 2002, ended up collecting data primarily for the extraordinarily weak phase of the monsoon over the Arabian Sea. Fortunately, the season of 2003 has turned out to be far better, with the anomaly (i.e. difference between the actual value and its long-term mean) of ISMR being positive and about 2% of the mean. The rainfall over the west coast in July 2003 was much higher than that in July 2002 (Figure 2a)

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**Figure 1.** Variation during 1979–2002 of the departure of all India June–September rainfall from its long-term mean. Dashed lines represent percentage departure by one standard deviation. Rainfall data for 1979–2001 are from <http://www.tropmet.res.in>, the website of the Indian Institute of Tropical Meteorology, Pune. Rainfall data of 2002 and 2003 are from Climate Diagnostic Bulletin, India Meteorological Department. El Niño and La Niña seasons are based on Climate Prediction Center, USA (<http://www.cpc.noaa.gov>.)

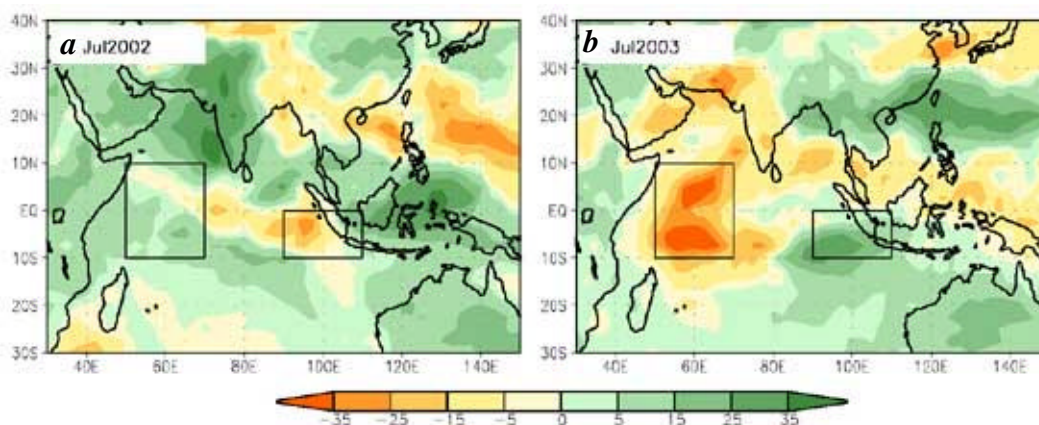


**Figure 2.** *a*, Difference in rainfall (expressed as a percentage of the long-term mean) between July 2003 and July 2002 in the subdivisions along the west coast of India. *b*, Variation of ISMR with the area-weighted average rainfall over the 5 subdivisions along the west coast of India for June–September.

and the anomaly of the all-India rainfall in July 2003 about 7%, which is consistent with the large contribution of the rainfall over the west coast to the interannual variation of ISMR (Figure 2*b*).

We next compare the deep convection in the atmosphere (i.e. deep cloud systems) over the Indian Ocean during July 2002–July 2003. Cloud systems over oceans and land can be readily gleaned from the daily maps of the outgoing long-wave radiation (OLR) derived from satellite measurements. Low values of OLR correspond to emission from higher levels and hence higher cloud

tops (and more rain when the clouds are deep), and OLR is used as a proxy for rainfall in the tropics<sup>12</sup>. Hence large negative (positive) anomalies in OLR are associated with large positive (negative) anomalies in rainfall over a region. The patterns of the anomalies of OLR for July 2002 and July 2003 are seen to be markedly different (Figure 3). The large anomalies of OLR over most of the Indian region west of 80°E appear to be associated with anomalies of the same sign over the western equatorial Indian Ocean and of the opposite sign over the eastern equatorial Indian Ocean. The contrasting patterns of 2002 and



**Figure 3.** OLR anomaly for (a) July 2002 and (b) July 2003. Note that positive anomaly of OLR corresponds to negative anomaly of rainfall. OLR data are from Climate Diagnostic Center, USA (<http://www.cdc.noaa.gov/>).

2003 suggest the possibility of a link of the variation of ISMR with the variation of deep convection over the equatorial Indian Ocean.

This is not surprising since the large-scale monsoon rainfall over the Indian region is associated with propagation of convective systems (either synoptic scale systems such as lows or depressions or the planetary scale cloud-bands in which they are embedded) which are generated over the warm ocean around the subcontinent<sup>13,14</sup>. Northward propagations of cloud-bands generated over the equatorial Indian Ocean occur throughout the summer monsoon season, beginning with the onset phase. Hence we expect the deep convection over the equatorial Indian Ocean to be critical for the monsoon.

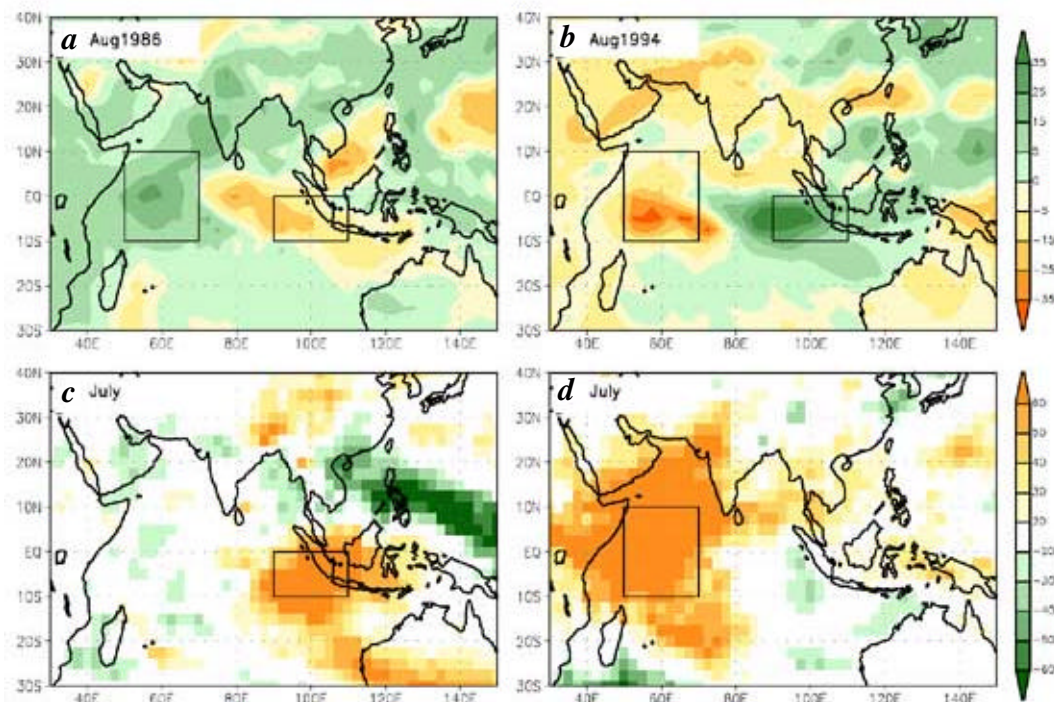
There have been several studies of the relationship of ISMR with the Indian Ocean. Most of the studies involve analysis of the relationship to the sea surface temperature (SST), since SST is believed to be an important parameter for deep clouding (deep convection) over the tropical oceans<sup>15</sup>. However, ISMR is found to be poorly correlated with the SST of different parts of the north Indian Ocean<sup>16,17</sup>. The Indian Ocean dipole mode characterized by anomalies of opposite sign in the SST and rainfall over the western part of the equatorial Indian Ocean (50°–70°E, 10°S–10°N, henceforth WEIO) relative to those over the eastern part (90°–110°E, 0°–10°S, henceforth EEIO), is believed to be linked to the Indian monsoon as well<sup>18,19</sup>. The dipole mode peaks in the autumn, after the summer monsoon. The relationship of the dipole mode and rainfall over the Indian Ocean and surrounding land areas has been studied using the dipole mode index (DMI), based on the difference in the SST anomalies of WEIO and EEIO<sup>18</sup>. The reduced impact of the El Niño in 1997 has been attributed to the presence of a positive dipole<sup>19</sup>. While DMI is highly correlated with rainfall over eastern Africa and western equatorial Indian Ocean, the correlation with the rainfall over the Indian region is positive, but poor<sup>18</sup>. The extent of the association of ISMR

with the dipole mode can be assessed by considering the anomalies of ISMR for seasons with ‘pure’ positive dipoles (i.e. in the absence of El Niño) and ‘pure’ negative dipoles (in the absence of La Niña)<sup>20</sup>. We find that while the ISMR anomalies for all pure positive dipoles are positive (ranging from 2 to 19.8%), for pure negative dipoles the ISMR anomaly is negative in only one out of five cases. Thus, none of the studies so far have found a strong association between ISMR and the Indian Ocean.

We present the results of an investigation of the links of the interannual variation of the monsoon with the atmospheric deep convection/circulation over the equatorial Indian Ocean, triggered by the contrasting OLR patterns for 2002 and 2003. We focus on the monsoon seasons with large deficit/excess in ISMR (i.e. magnitude of anomaly > standard deviation) during 1979–2003 for which continuous satellite data are available. It should be noted that excess rainfall can occur in the absence of La Niña (e.g. 1994 in Figure 1) and droughts do occur in the absence of El Niño (e.g. 1979 in Figure 1). In fact, of the 22 droughts that occurred during 1871–2001, only 11 were associated with El Niño<sup>21</sup>. We need to understand whether the events over the Indian Ocean play a role in such droughts/excess rainfall seasons.

### Equatorial Indian Ocean Oscillation and ENSO

We find OLR patterns similar to 2002 and 2003 (with the OLR anomalies over the western part of the equatorial Indian Ocean being opposite to that over the eastern part) in several summer monsoon seasons (e.g. the patterns for August 1986 and 1994; Figure 4). The correlation of OLR with the average OLR over WEIO (Figure 4) is high over the eastern Arabian Sea and the western part of the Indian region. The OLR over the EEIO is seen to be negatively correlated with that over the Bay of Bengal and also the Indian monsoon zone<sup>14</sup>.



**Figure 4.** OLR anomaly patterns (a) August 1986 and (b) August 1994. Correlation for July of OLR with respect to average OLR over (c) EEIO (90–110°E, 10°S–EQ), and (d) WEIO (50–70°E, 10°S–10°N).

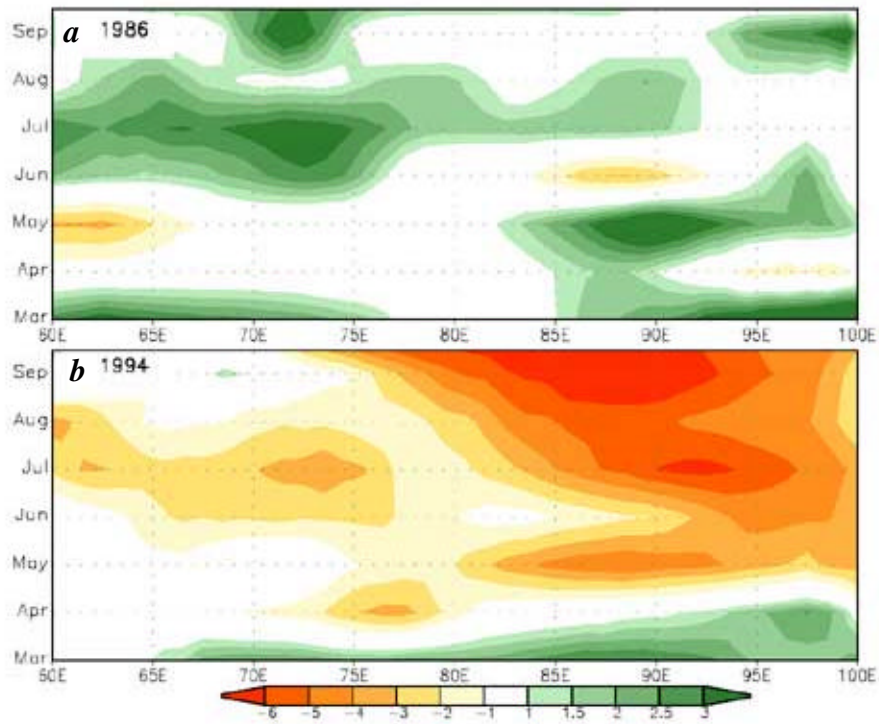
The anomalies of OLR over EEIO tend to be opposite in sign to the anomalies of OLR over WEIO for each of the summer monsoon months, and the OLR over EEIO is negatively correlated with that over WEIO. The anomalies of the sea-level pressure and the zonal (east-west) component of the surface wind along the equator are consistent with the OLR anomalies. Thus, when deep convection is enhanced over WEIO and reduced over EEIO, the pressure is reduced over the western part and enhanced over the eastern part. The anomalous pressure gradient (with pressure increasing from west to east) is associated with easterly (i.e. from the east to the west) anomalies in the zonal wind (e.g. 1994 in Figure 5). On the other hand, when deep convection is enhanced over the eastern part, there are westerly anomalies of the zonal wind at the equator (e.g. 1986 in Figure 5). We call the oscillation between these two states as the Equatorial Indian Ocean Oscillation (henceforth EQUINOO). We use an index of the EQUINOO based on the anomaly of the zonal component of the surface wind at the equator (60°–90°E, 2.5°S–2.5°N) which is highly correlated (coefficient 0.81) with the difference between OLR of WEIO and EEIO. The zonal wind index (henceforth EQWIN) is taken as the negative of the anomaly.

In the coupled ocean–atmosphere system, the anomalies of the wind, OLR and SST are interrelated and so are EQUINOO and the dipole mode. For June–September, the correlation between DMI and EQWIN is high (coefficient 0.71). However, the association between EQWIN

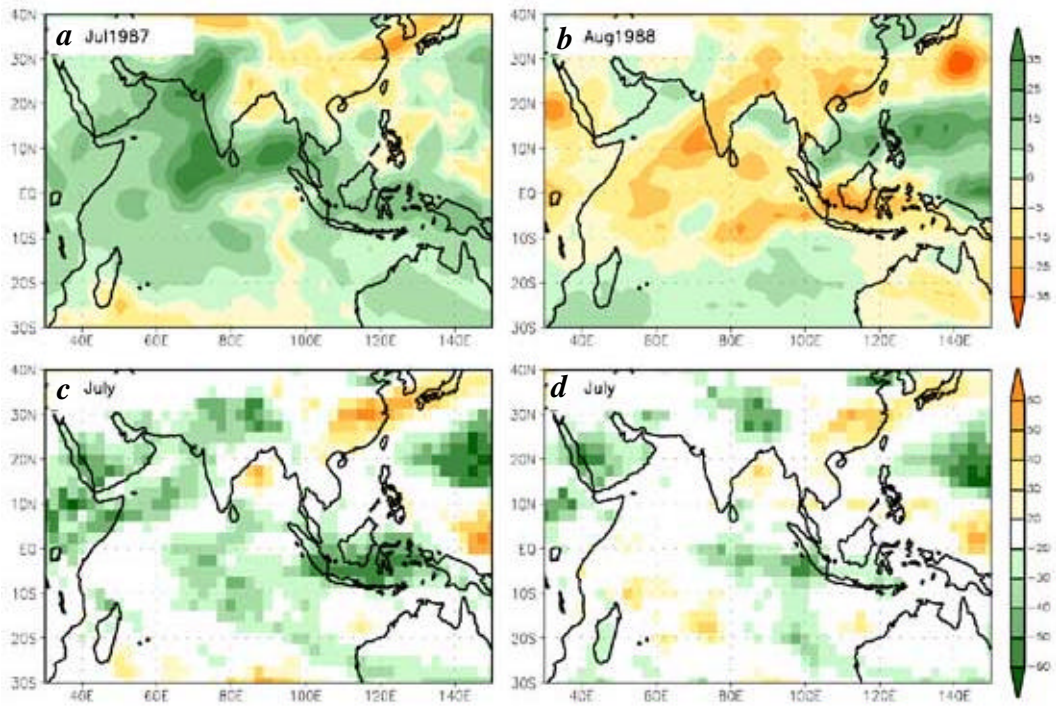
and ISMR is stronger than that between DMI and ISMR. Whereas in only one out of five ‘pure’ negative dipoles (based on DMI)<sup>20</sup> the ISMR anomaly was negative, we find that in every season with large positive (negative) EQWIN, the ISMR anomaly is positive (negative). This difference arises because, although atmospheric circulation and SST are interrelated, large values of EQWIN and DMI do not always occur in the same seasons, since there are lags between the changes that occur in the atmosphere and oceans. In this study we restrict our attention to the association with the atmospheric circulation and in particular, EQWIN.

The overall impact of a typical El Niño (La Nina) is the suppression (enhancement) of deep convection over almost the entire equatorial Indian Ocean as well as the Indian region<sup>22,23</sup>. This is illustrated in Figure 6 by the OLR patterns during the El Niño of 1987 and La Nina of 1988. The correlation patterns for July, with respect to the OLR of central and east Pacific (over which large changes in deep convection occur in association with ENSO<sup>24</sup>), are also shown in Figure 6. As an index of ENSO we use the OLR anomaly over central Pacific (CPOLR) rather than east Pacific, since the deep convection over central Pacific is better correlated with that over the Indian region.

Composites of El Niño and La Nina<sup>23,25</sup> suggest that El Niño (La Nina) events are associated with easterly (westerly) anomalies of the zonal wind along the equator. Thus we expect EQWIN to be negatively correlated with



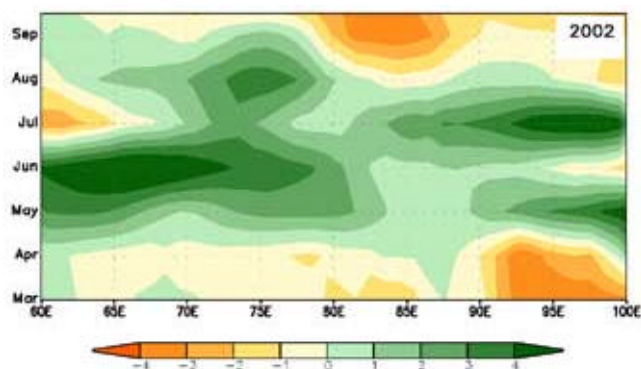
**Figure 5.** Variation with longitude of the anomaly of the zonal component of the surface wind averaged over 2.5°S to 2.5°N during March–September of (a) 1986 and (b) 1994. Data from Florida State University (<http://www.coaps.fsu.edu/>).



**Figure 6.** Anomaly patterns of OLR for (a) July 1987 and (b) August 1988. Correlation for July of OLR with the average OLR over (c) central Pacific (160°E–150°W, 5°S–5°N) and (d) east Pacific (150–90°W, 5°S–5°N).



**Figure 7.** ISMR anomaly, EQWIN and CPOLR anomaly (each normalized by the standard deviation) during June–September for years with large deficit in ISMR, 1997, and large excess in ISMR in order of increasing ISMR.



**Figure 8.** Variation with longitude of the anomaly of the zonal component of the surface wind averaged over 2.5°S to 2.5°N during March–September of 2002.

CPOLR. However, we find that for a large fraction of the seasons (10 out of 24), CPOLR and EQWIN have the same sign. This supports the suggestion that a significant part of the variability of the Indian Ocean coupled system is independent of ENSO<sup>18,26</sup>.

### ISMR, ENSO and EQUINOO

The ISMR anomaly, the CPOLR and EQWIN for all the summer monsoon seasons with a large ISMR anomaly and the special season of 1997, are depicted in Figure 7 in order of increasing ISMR. It should be noted that while the indices CPOLR and EQWIN give an indication of the strength of ENSO or EQUINOO, they are not expected to give quantitative assessments of relative impacts

on ISMR. In 1997, EQWIN and CPOLR are comparable but opposite in sign, and the ISMR anomaly is small. In fact, each season with a large negative (positive) anomaly in ISMR is seen to be associated with unfavourable (favourable) phases of either ENSO or EQUINOO, or both.

In all the three seasons with excess monsoon rainfall, the phase of the EQUINOO was favourable. Of these, ENSO was also favourable in 1988 (La Nina), whereas in 1983 excess rainfall occurred despite the ENSO phase being unfavourable. In 1994, the effect of ENSO was small and the excess rainfall can be attributed to the favourable phase of EQUINOO. Of the six seasons with deficit ISMR, in 1982 and 1987, the EQUINOO was favourable but not as strong as in 1997 and could not counter the impact of the El Niño. In 1979, 1985 and 1986 the phase of EQUINOO was unfavourable but the phase of the ENSO was not unfavourable. In the monsoon season of 2002, although the El Niño was weak, the EQUINOO was also unfavourable and a severe drought occurred. Thus with EQUINOO we can ‘explain’ not only the droughts that occurred in the absence of El Niño or in the presence of a weak El Niño, but also excess rainfall seasons in which ENSO did not dominate.

From the point of view of prediction, an important question arises: Did the conditions prior to the summer monsoon, i.e. in April/May contain any clues about the unfavourable phase of EQUINOO in 2002? The evolution of the anomalies of the zonal wind along the equator (on which EQWIN is based) during March–September 2002 is shown in Figure 8. The signal for unfavourable anomalies is seen from mid-April. Thus, had we known more about the association of ISMR with EQUINOO, we could have made an educated guess about the season of 2002

having deficit rainfall. However, before this association with EQUINOO can be used for prediction, it is necessary to investigate it further with more analysis of observations and models which can simulate the observed association.

## Summary

We conclude that there is a strong association of the large anomalies in the Indian monsoon rainfall with EQUINOO and ENSO. It is difficult to assess this association quantitatively with the sample of only 24 years. Nevertheless, we believe that since EQUINOO, along with ENSO, can 'explain' all the seasons with large deficit or excess in the Indian monsoon rainfall during the satellite era, it is important to explore EQUINOO further with models and identify the mechanisms for impact on the monsoon. For better monsoon predictions we need to unravel the cause-effect relationships and monitor those facets of the EQUINOO and ENSO which can influence the monsoon.

1. Centre for Monitoring Indian Economy, Economic Intelligence Service, 2003.
2. Gadgil, Sulochana, *et al.*, On forecasting the Indian summer monsoon: the intriguing season of 2002. *Curr. Sci.*, 2002, **83**, 394–403.
3. Sikka, D. R., Some aspects of the large-scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1980, **89**, 179–195.
4. Pant, G. B. and Parthasarathy, B., Some aspects of an association between the southern oscillation and Indian summer monsoon. *Arch. Meteorol. Geophys. Bioklimetol.*, 1981, **29**, 245–251.
5. Rasmusson, E. M. and Carpenter, T. H., The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Weather Rev.*, 1983, **111**, 517–528.
6. Rasmusson, E. M. and Carpenter, T. H., Variations in the tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Weather Rev.*, 1982, **110**, 354–384.
7. Philander, S. G. H., *El Niño, La Nina, and the Southern Oscillation*, Academic Press, San Diego, 1990.
8. Cane, M. A., Zebiak, S. E. and Dolan, S. C., Experimental forecasts of El Niño. *Nature*, 1986, **321**, 827–832.
9. Parthasarathy, B., Munot, A. A. and Kothawale, D. R., Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological subdivisions, Indian Institute of Tropical Meteorology, Pune, 1995.
10. Kumar, K. K., Rajagopalan, B. and Cane, M. A., On the weakening relationship between the Indian monsoon and ENSO. *Science*, 1999, **284**, 2156–2159.
11. Arabian Sea Monsoon Experiment Science Plan, Department of Science and Technology, Govt. of India, New Delhi, 2001.
12. Kidder, S. Q. and Vonder Haar, T. H., *Satellite Meteorology – An Introduction*, Academic Press, San Diego, 1995, p. 457.
13. Sikka, D. R. and Gadgil, Sulochana, On the maximum cloud zone and the ITCZ over India longitude during the southwest monsoon. *Mon. Weather Rev.*, 1980, **108**, 1122–1135.
14. Gadgil, Sulochana, The Indian Monsoon and its variability. *Annu. Rev. Earth Planet. Sci.*, 2003, **31**, 429–467.
15. Bjerknes, J., Atmospheric teleconnections from the equatorial Pacific. *Mon. Weather Rev.*, 1969, **97**, 163–172.
16. Shukla, J. and Misra, B., Relationship between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India. *Mon. Weather Rev.*, 1977, **105**, 998–1002.
17. Rao, R. G. and Goswami, B., International variations of SST over the Arabian Sea and the Indian monsoon: A new perspective. *Mon. Weather Rev.*, 1988, **116**, 558–568.
18. 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.
19. Ashok, K., Guan, Z. and Yamagata, T., Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.*, 2001, **28**, 4499–4502.
20. Yamagata, T., Behera, S., Rao, S. A., Guan, Z., Ashok, K. and Saji, H., The Indian Ocean dipole: a physical entity. *CLIVAR Exchanges*, 2002, **24**, 15–18.
21. Kumar, K. R., Kumar, K. K., Ashrit, R. G., Patwardhan, S. K. and Pant, G. B., *Climate Change in India* (eds Shulka *et al.*), Tata McGraw Hill, New Delhi, 2002, pp. 24–75.
22. Hastenrath, S., Nicklis, A. and Greischar, L., Atmospheric hydro-spheric mechanisms of climate anomalies in the western equatorial Indian Ocean. *J. Geophys. Res.*, 1993, **98**, 20219–20235.
23. Reason, C. J., Allan, C. R. J., Lindesay, J. A. and Ansell, T. J., ENSO and climatic signal signals across the Indian Ocean basin in the global context: Part 1, interannual composite patterns. *Int. J. Climatol.*, 2000, **20**, 1285–1327.
24. Wallace, J. M. *et al.*, On the structure and evolution of ENSO related climate variability in the tropical Pacific: lessons from TOGA. *J. Geophys. Res.*, 1998, **103**, 14241–14259.
25. Ropelewski, C. F. and Halpert, M. S., Precipitation patterns associated with the high index phase of the Southern Oscillation. *J. Climate*, 1989, **2**, 268–284.
26. Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R., Coupled oceanic-atmospheric dynamics in the Indian Ocean during 1997–98. *Nature*, 1999, **401**, 356–360.

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