

Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation

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[1] It is well known that anomalies of the Indian Summer Monsoon Rainfall (ISMR) are linked to El Niño and Southern Oscillation (ENSO). We show that large anomalies of the ISMR are also linked to the Equatorial Indian Ocean Oscillation (EQUINOO) between states with enhancement/suppression of atmospheric convection over the western part of the equatorial Indian Ocean with suppression/enhancement over the eastern part and associated changes in the anomaly of the zonal wind along the equator. EQUINOO is the atmospheric component of the coupled Indian Ocean Dipole mode. There is a strong relation between the large anomalies of ISMR and a composite index which is a linear combination of the indices for ENSO and EQUINOO with all seasons with large deficits (excess) characterized by small (large) values of the index. However, the variation of ISMR within one standard deviation is more complex and does not appear to be related to the composite index. *INDEX TERMS:* 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 1812 Hydrology: Drought; 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Niño; 9340 Information Related to Geographic Region: Indian Ocean. **Citation:** Gadgil, S., P. N. Vinayachandran, P. A. Francis, and S. Gadgil (2004), Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation, *Geophys. Res. Lett.*, 31, L12213, doi:10.1029/2004GL019733.

1. Introduction

[2] The rainfall received over India during the four summer months of June–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 billions of dollars. Thus, prediction of the Indian summer monsoon rainfall (i.e., rainfall during June to September averaged over the Indian region [Parthasarathy *et al.*, 1995] (hereinafter referred to as ISMR)) remains an important concern. In the 80s, the strong link with ENSO, manifested as 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 Niña, was clearly established [Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983]. For example, during

1958–1988 all the El Niño events were droughts (with deficit in ISMR more than one standard deviation) and all the La Niña events were associated with excess ISMR. 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 and it was suggested that the relationship between the Indian monsoon and ENSO had weakened in the recent decades [Kumar *et al.*, 1999]. Although an El Niño event was known to be developing in 2002, none of the predictions for 2002 suggested a large deficit in the Indian monsoon rainfall [Gadgil *et al.*, 2002]. The experience of 1997 and 2002 suggests that we do not as yet understand adequately the response of the monsoon to El Niño. It should also be noted that large (henceforth, of magnitude greater than one standard deviation) deficits/excess do occur in the absence of El Niño/La Niña. In fact, of the 22 (19) large negative (positive) ISMR anomalies that occurred during 1871–2001, only 11(8) were associated with El Niño(La Niña) [Kumar *et al.*, 2002].

[3] A special feature of the monsoon of 2002 was an unprecedented deficit of 49% in the rainfall in the peak monsoon month of July leading to the large deficit in ISMR. The patterns of the anomalies of OLR and surface wind for July 2002 are shown in Figure 1 with those for July 1997 (El Niño but near normal monsoon rainfall), August 1986 (deficit rainfall) and August 1994 (excess rainfall). There is a marked difference between the anomaly patterns of 2002 and 1997 not only over the Indian region, but also over the equatorial Indian Ocean. Over the equatorial Indian Ocean, the OLR anomalies are positive over the western part and negative over the eastern part in 2002 and 1986, and westerly wind anomalies occur along the equator over the central part. The patterns for 1997 and 1994 are opposite in phase with negative OLR anomalies over the western part and easterly wind anomalies over central equatorial Indian Ocean. The contrasting OLR patterns for the deficit and excess monsoon seasons of 1986 and 1994 suggest the possibility of a link of ISMR with the variation of convection over the equatorial Indian Ocean.

[4] We expect the convection over the equatorial Indian Ocean to be critical for the monsoon in view of the contribution of northward propagations of tropical convergence zones (TCZ) generated over this region to the summer monsoon rainfall over the Indian region [Sikka and Gadgil, 1980; Gadgil, 2003]. However, convection over the equatorial Indian Ocean can also be unfavourable because of the competition between the oceanic and continental TCZ [Gadgil, 2003, and references therein]. The OLR patterns of 1986 and 1994 suggest that convection over the western part of the equatorial Indian Ocean is

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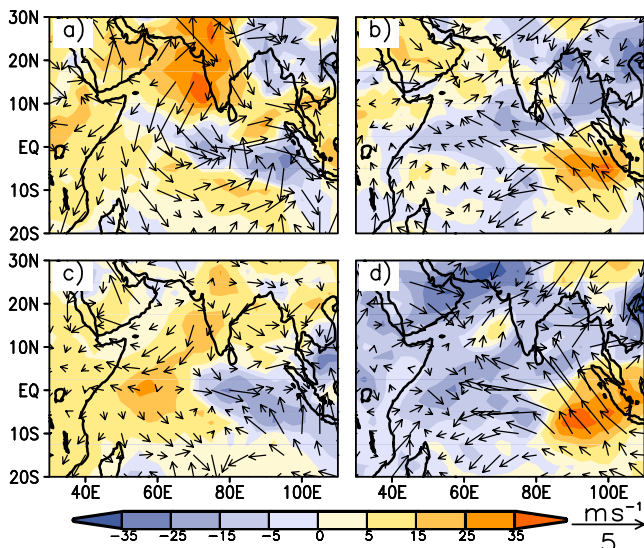


Figure 1. OLR (Wm^{-2}) and surface wind anomaly (ms^{-1}) patterns for (a) July 2002, (b) July 1997, (c) August 1986, and (d) July 1994.

favourable for the monsoon while that over the eastern part is unfavourable. This is supported by the correlation relative to the OLR over western and eastern parts of equatorial Indian Ocean for July, August (Figures 2a and 2b).

[5] Suppression (enhancement) of convection over the eastern (western) part and easterly (westerly) anomalies of the zonal component of the surface wind over the equatorial region are characteristics of the positive (negative) phase of the Indian Ocean Dipole (IOD) mode [Saji et al., 1999; Webster et al., 1999]. This coupled mode is characterized by anomalies of opposite sign in the sea surface temperature (SST) and sea surface height (SSH) in the western (50° – 70°E ., 10°S – 10°N ., henceforth WEIO) and eastern (90° – 110°E ., 0° – 10°S ., henceforth EEIO) parts of the equatorial Indian Ocean. The patterns in Figure 1 suggest the presence of a positive (negative) phase of the dipole mode in 1994, 1997 (1986, 2002). The relationship of the IOD 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. 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 poor [Saji et al., 1999]. The presence of a positive dipole in 1994 and 1997

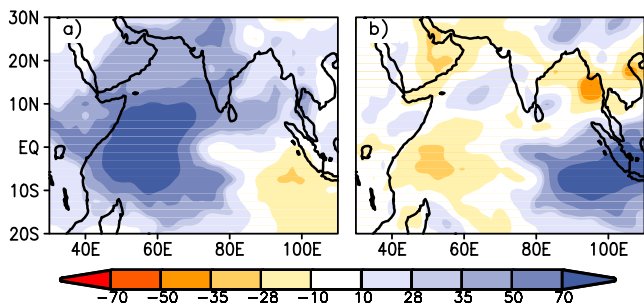


Figure 2. Correlation ($\times 100$) for July and August of OLR with the average OLR over (a) WEIO and (b) EEIO. Values above 28 is significant at 95%.

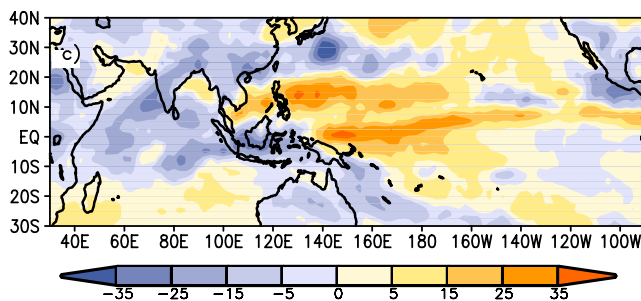


Figure 3. OLR (Wm^{-2}) anomaly pattern for August 1988.

has been documented and the reduced impact of the El Niño in 1997 has been attributed to it [Ashok et al., 2001]. However, the impact of the negative phase of the dipole mode on ISMR has not been elucidated as yet.

[6] The impact of ENSO on convection over the Indian Ocean as well as the Indian region is suppression of convection in the El Niño phase and enhancement of convection in the La Niña phase (e.g., Figure 3 for the La Niña of 1988). The interplay of ENSO and the IOD mode can lead to different patterns of SST and OLR anomalies over the equatorial Indian Ocean (depending on the phases and strengths of the two modes) with different implications for the Indian Monsoon. We present the results of an investigation of the links of the interannual variation of ISMR, during 1958–2003, with the atmospheric convection/circulation over the equatorial Indian Ocean and ENSO.

2. Data

[7] The following data sets were used in this study (i) ISMR from [Parthasarathy et al., 1995] and update from

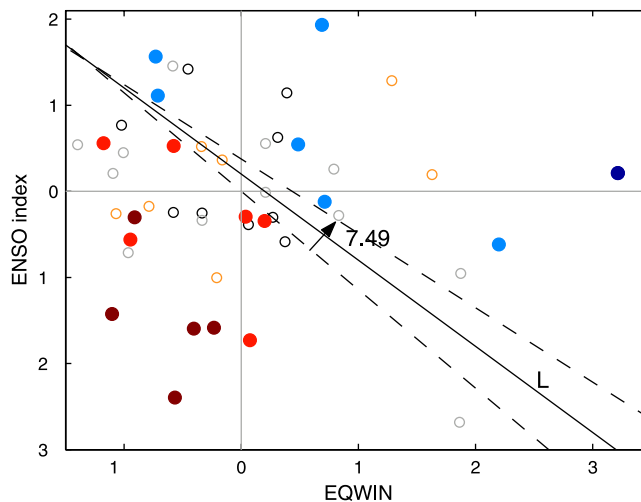


Figure 4. Each season during 1958–2003 is shown on the phase plane of the June to September average of the ENSO index (negative of Nino 3.4 index) and EQWIN. The corresponding ISMR anomaly (normalized by the standard deviation) is represented with different symbols: large dark blue (red) closed circles for values above (below) 1.5 (–1.5), blue (red) closed circles for values between 1 (–1) and 1.5 (–1.5), small black (orange) open circles for values between 0.25 (–0.25) and 1 (–1) and small gray open circles for values between –0.25 and 0.25.

the web site of Indian Institute of Tropical Meteorology (<http://www.tropmet.res.in/>); the rainfall for 2002 from the operational data in Climate Diagnostic Bulletin, India Meteorological Department (ii) NINO 3.4 index i.e., the SST anomaly over the Nino3.4 region (120°W–170°W, 5°S–5°N, obtained from Climate Analysis Section, National Center for Atmospheric Research, USA (<http://www.cgd.ucar.edu/>) (iii) the OLR data from Climate Diagnostic Center, USA (<http://www.cdc.noaa.gov/>) (iv) the surface wind data from National Center for Environmental Prediction [Kalnay *et al.*, 1996] (<http://www.cdc.noaa.gov/>) and (v) DMI from <http://www.jamstec.go.jp>. We use the NINO 3.4 index rather than the Nino3 index since the Nino3.4 index is better correlated with ISMR. We take ENSO index as negative of Nino 3.4 index, normalized by the standard deviation, so that positive values of the ENSO index are favourable for the monsoon.

3. IOD and EQUINOO

[8] For each of the summer monsoon months, the OLR over EEIO is negatively correlated with that over WEIO and the anomalies of OLR over these two regions tend to be opposite in sign. The anomalies of the sea level pressure and the zonal component of the surface wind along the equator are consistent with the OLR anomalies. Thus, when convection is enhanced in the western part (positive phase of the IOD mode), the anomalous pressure gradient is westward and there are easterly anomalies in the zonal wind (e.g., 1994, 1997 in Figure 1). On the other hand, when convection is enhanced over the eastern part (negative phase of the IOD mode), there are westerly anomalies of the zonal wind at the equator (e.g., 1986, 2002 in Figure 1). EQUINOO is the oscillation between these two states. We use an index of the EQUINOO which is the negative of the anomaly of the zonal component of the surface wind at the equator (60°E–90°E, 2.5°S–2.5°N) normalized by its standard deviation. This zonal wind index (henceforth EQWIN) is highly correlated (coefficient 0.81) with the difference between OLR of WEIO and EEIO.

[9] In the coupled ocean-atmosphere system, the anomalies of the wind, OLR and SST are interrelated. EQUINOO is the atmospheric component of the coupled IOD mode. EQWIN and DMI, which are measures of different facets of this mode, are also significantly correlated for June–September of 1958–1997 (coefficient 0.56). However, this correlation arises primarily from high positive values of both indices in the positive dipole events of 1961, 94 and 97. If these years are omitted, in a large proportion of the years the two indices have opposite signs (particularly in the negative phase of EQWIN) and the correlation drops to 0.32. Such differences in the two indices could be a consequence of the physical processes that lead to the development of the dipole SST anomalies. These anomalies are initiated by the wind anomalies along the equator [Vinayachandran *et al.*, 1999; Murtugudde *et al.*, 2000]. The canonical dipole mode event peaks after the summer monsoon, in the autumn [Saji *et al.*, 1999]. However, every event of large wind anomalies during the summer monsoon is not followed by intensification of the SST anomalies to a dipole stage. For example, the large wind anomalies in the summer of 2003 did not lead to an IOD event. It should also

be noted that the SST anomalies of the negative dipole events are generally weaker than those for positive events [Vinayachandran *et al.*, 2002] due to the asymmetry in the response of SST to upwelling and downwelling.

[10] For 1958–97, while the ISMR is significantly correlated with EQWIN (coefficient 0.42), the correlation of ISMR with DMI is poor (–0.035). We therefore use EQWIN, which is the index of EQUINOO, for this study.

4. ISMR, ENSO, and EQUINOO

[11] We consider the relationship of anomalies of ISMR to the June to September averages of the EQUINOO index (EQWIN) and the ENSO index. ISMR is found to be significantly correlated to ENSO index (correlation coefficient 0.52) as well as EQWIN (correlation coefficient 0.43). ENSO index is poorly correlated with EQWIN (coefficient –0.09). The partial correlation of ISMR with EQWIN (after removing ENSO effect) is 0.56, whereas that with ENSO index (after removing EQUINOO effect) is 0.63.

[12] In Figure 4, the category of ISMR for each season during 1958–2003, is shown in the phase plane of the ENSO index and EQWIN. We consider first the extreme years i.e., the years with large excess or deficits (droughts). For the period 1979–2002, [Gadgil *et al.*, 2003] had shown that each large positive (negative) anomaly of ISMR is associated with the favourable (unfavourable) phase of either ENSO or EQUINOO or both; and that the largest anomalies of ISMR occur when these two modes reinforce each other. This result is also seen to be valid for the period 1958–2003.

[13] The most striking feature of the distribution of extreme years is the clear separation between the years with excess and deficits with all the surplus years located above a certain line in the phase plane (the line L in Figure 4). This suggests that an appropriate index would be a composite index, which is a linear combination of the ENSO index and EQWIN. To study the relation between the composite index and ISMR, we use order statistics [Feller, 1967] i.e., we order years according to the composite index. If the ISMR is related to the composite index, we expect the years with low rainfall to have lower value of the composite index. To get a quantitative assessment, we consider all possible pairs of years, each pair comprising one year with a large excess and one with a large deficit. Then, we find out the fraction of such pairs in which the drought years has a lower composite index than the years with surplus.

[14] Our first striking result is obtained by considering extreme years ordered by the composite index. We see that each of the 11 drought years have lower composite index than each of the 7 surplus years. The probability of this happening by chance (i.e., when ISMR is unrelated to the composite index) is $7!11!/18!$, i.e., 0.00314%, which is extremely small. Thus there is a very significant relation between the composite index and extreme ISMR events. However, we need to correct the estimated significance of the composite index, to allow for the fact that the index was chosen using the data used to validate it. For this we should estimate the probability (in the absence of a relation) that some linear combination of EQWIN and ENSO index gives an ordering with all droughts before all surpluses. We make a very conservative correction for this. We note that the line

that gives the extreme order is not unique, but any one with slope in a sector of 7.49 degrees gives this ordering (Figure 4). We get an upper bound of the probability of this happening by chance. Observe that if we pick 50 evenly spaced points at random, at least one of them lies in the above sector as $7.49 > 360/50$. So at least one of the corresponding linear combinations separates droughts from surpluses. The probability that, of fifty lines with evenly spaced slopes, at least one separates droughts and surpluses, is at most 50 times 0.00314% i.e., 0.157% which is still a very small number. Therefore, we may conclude that there is a very strong relation between the composite index and the occurrence of large excess or deficit ISMR. If we consider the relationship of the extreme events to only the ENSO index (or EQWIN) we find that of the possible 77 pairs, 11(14) pairs have deficit years with a larger value of the index than that for the surplus year. Thus the relationship to the composite index is far stronger than that to the index of either the ENSO or the EQUINOO. We note that the coefficients of ENSO index and EQWIN (each of which is normalized) in the composite index are almost equal. This suggests that contribution of the two modes, ENSO and EQUINOO, to large anomalies of ISMR are comparable.

[15] Consider now the years with small (magnitude between 0.25 of and one standard deviation) deficits and small surpluses. Of the 63 pairs of such years with one deficit year and the other a surplus one, in 30 cases the surplus year has a smaller value for the composite index. This is slightly less than half of the pairs, so clearly the relationship, if any, is very weak. The same holds for relationship to the separate ENSO index and EQWIN since the numbers of such pairs are 31 and 30 respectively. Thus there appears to be no relation between ISMR anomalies and either the ENSO index or EQWIN or the composite index when the variation of ISMR is within one standard deviation.

[16] We have so far considered whether droughts are associated with low values of the index and years of large surplus with large values. We now consider the converse question - do years that have a low (high) value of the composite index tend to have large deficit (excess) ISMR? We find that the five years with the lowest value of the composite index are all droughts. This is a very significant relation as the chance of this happening purely by chance is 0.0632%, given that droughts occurred on 11 of the 48 years. On the other hand, if we consider the years with the five largest values of the composite index, only two of them have large surpluses. Thus while low values of the composite index are likely to be associated with droughts, the relationship of excess rainfall to high values of the composite index is weaker.

5. Conclusions

[17] The major result is the presence of a strong relation between large deficits/excess in ISMR and a composite index based on indices of ENSO and EQUINOO. Since the two indices are a measure of two modes of the coupled system, this suggests that the impact of the two modes on ISMR is additive. Events of exceptionally large deficits or excess occur when the amplitude is large and the two modes act in phase so that they reinforce one another. Since the association between large ISMR anomalies and the two modes is now established, possibility of using the links for

prediction needs to be explored. We find that the negative phase of EQUINOO characterizing the drought of 2002, commenced in April. Since the ENSO phase was also unfavourable, we should have anticipated a deficit monsoon. This suggests that unravelling the cause-effect relationships and monitoring the important facets of the two modes could lead to better prediction of the monsoon

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