Monsoon variability: Links to major oscillations over the equatorial Pacific and Indian oceans

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In this article, we first discuss our perception of the factors which are critical for inter-annual variation of the Indian summer monsoon rainfall and the major milestones leading to this understanding. The nature of the two critical modes for monsoon variability, viz. El Nino Southern Oscillation and equatorial Indian Ocean Oscillation is considered and their links to the monsoon elucidated. We suggest possible reasons for the rather poor skill of simulation of the interannual variation of the Indian summer monsoon rainfall by atmospheric general circulation models, run with the observed sea surface temperature as boundary condition. We discuss implications of what we have learned for the monsoon of 2006, and possible use of information on the two important modes for prediction of the rainfall in all or part of the summer monsoon season. We conclude with our view of what the focus of research and development should be for achieving a substantial improvement in the skill of simulation and prediction of the Indian summer monsoon rainfall in the near future.

Keywords: El Nino Southern Oscillation, Indian monsoon, monsoon variability, Indian Ocean.

IT is well known that the variation of the Indian summer monsoon rainfall (ISMR) from year to year (Figure 1) has a large impact on the agricultural production and hence the economy of the country. In the colonial era, the Indian economy was described as a gamble on the monsoon rains. With planned development since independence, the contribution of agriculture to the Gross Domestic Product (GDP) decreased substantially and led to the expectation that the impact of the monsoon on the economy would have also decreased. However, a recent analysis of the variation of the GDP and the monsoon[1] has revealed that the impact of severe droughts on GDP has remained between 2 and 5% of GDP throughout. A significant finding of this study is the asymmetry in the response to monsoon variation, with the magnitude of the impact on food-grain production (IFGP) and the GDP (IGDP) of deficit rainfall being larger than that for surplus rainfall (Figure 2). It has been suggested that a possible reason for the rela-

tively low response of foodgrain production to average and above average monsoon rainfall post-1980, is that the strategies that would allow farmers to reap benefits of the good rainfall years are not economically viable in the current mileu. Such strategies (such as adequate investments in fertilizers and pesticides over rain-fed areas) would become economically viable if reliable predictions for 'no droughts' could be generated.

Thus prediction of the interannual variation of ISMR and particularly for the occurrence/nonoccurrence of the extremes (i.e. droughts and excess rainfall seasons) continues to be extremely important. However, the skill of atmospheric and coupled models in predicting the Indian monsoon rainfall is not satisfactory, and the problem is particularly acute as these models fail to predict the extremes[2]. For example, none of these models could predict the recent droughts of 2002 and 2004. It is important to
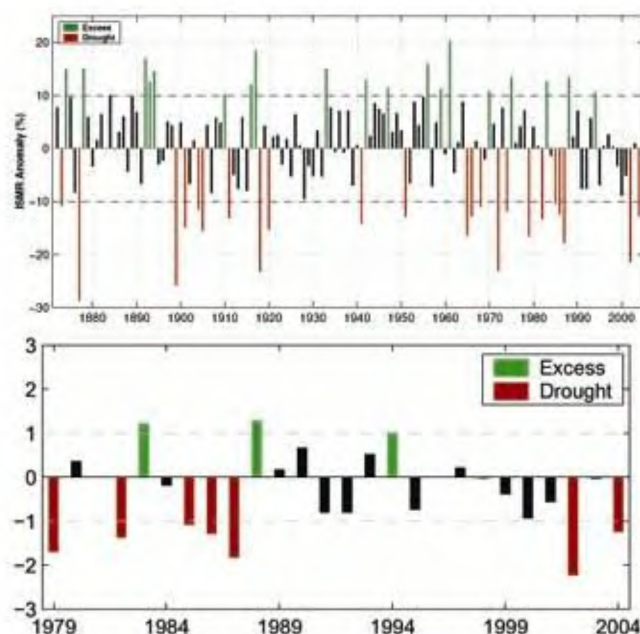

Figure 1. Variation of the anomaly of all-India summer monsoon (June–September) rainfall from 1871–2004 (above, as percentage of mean) and 1979–2004 (below, normalized by standard deviation). Droughts, i.e. years with deficit larger than 10% of the average are shown as red and excess monsoon seasons, i.e. with excess larger than 10% of the average are shown as green.

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note that the breakthroughs in seasonal forecasting over the tropics have come from the phenomenal progress since the eighties in the understanding of the physics of El Nino Southern Oscillation (ENSO), the dominant signal of interannual variation of the coupled atmosphere–ocean system over the Pacific. The elucidation of the nature of ENSO, unravelling of the underlying mechanisms[3–5] led to the development of models to a level at which they could simulate the phenomenon and its impacts on the climate of different regions realistically. Understanding, simulating and hence predicting the variability of the Indian monsoon is clearly the next frontier in tropical variability.

A major advance in our understanding of the interannual variation of the monsoon occurred in the eighties with the discovery (or rediscovery) of a strong link with ENSO. ENSO involves oscillation between a warm phase, El Nino, characterized by abnormal warming of surface ocean waters of the central and eastern Pacific and enhanced convection in the atmosphere above, and a cold phase, La Nina, characterized by abnormal cooling of these waters and suppressed convection in the atmosphere above. Studies[6–8] have shown that there is an increased propensity of droughts during El Nino and of excess rainfall during La Nina. To study the relationship of the ISMR with ENSO, we use an ENSO index based on the SST anomaly of the Nino 3.4 region (120–170 W, 5 S–5N), since the magnitude of the correlation coefficient of ISMR with the convection over the central Pacific is higher than that with convection over the east Pacific (Figure 3). The ENSO index is defined as the negative of the Nino 3.4 SST anomaly (normalized by the standard deviation), so that positive values of the ENSO index imply a phase of ENSO favourable for the monsoon. El Ninos are associated with ENSO index less than –1.0 and La Nina with ENSO index greater than 1.0.

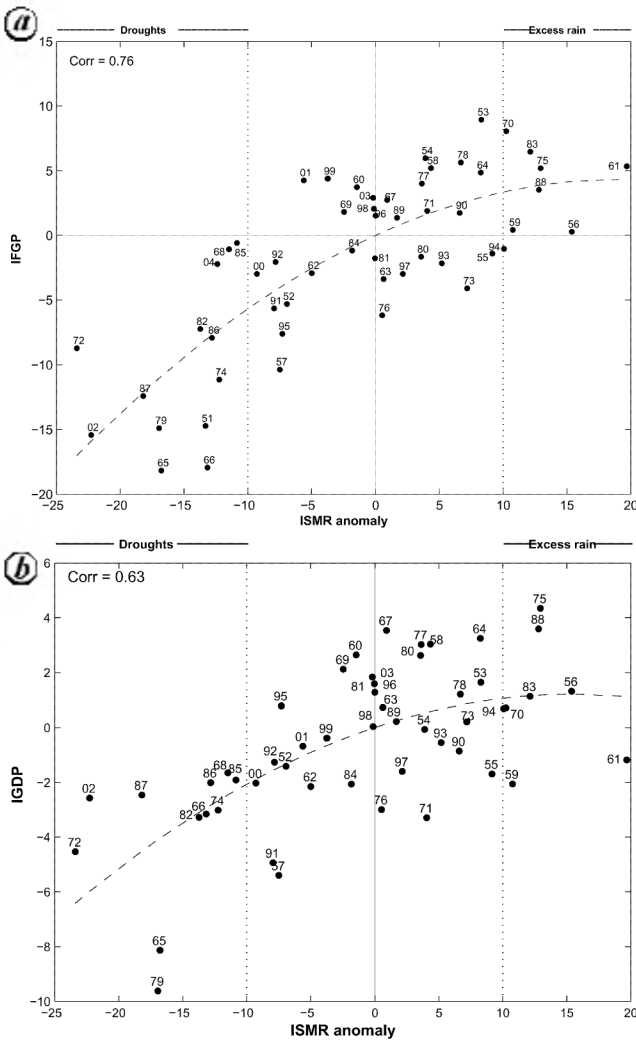The relationship of ISMR with ENSO index for the period 1958–2004 is shown in Figure 4 in which the

Figure 2. *a*, Variation of the impact on foodgrain production, IFGP. *b*, Variation of the impact on GDP, IGDP with that of the monsoon rainfall anomaly; numbers represent the years.
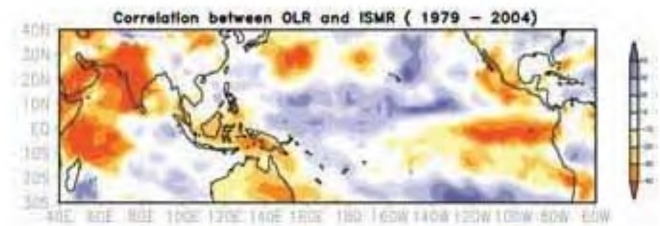
Figure 3. Pattern of correlation between outgoing longwave radiation (OLR, which is inversely related to convection and clouding) and ISMR for the period 1979–2004.
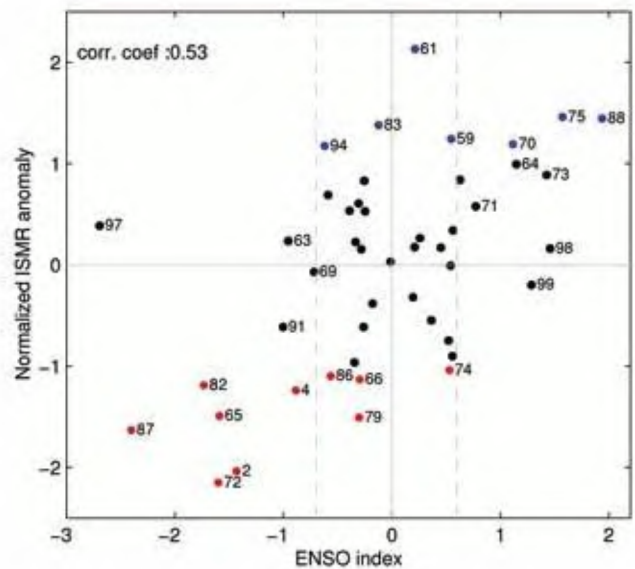
Figure 4. Normalized ISMR anomaly versus ENSO index for all the June–September seasons between 1958 and 2004. Red represents droughts, i.e. seasons with ISMR deficit greater than 1 standard deviation in magnitude; whereas blue represents excess monsoon seasons, i.e. with ISMR anomaly greater than 1 standard deviation.

droughts and excess rainfall seasons of ISMR can also be distinguished. It is seen that when the ENSO index is favourable (>0.6), there are no droughts and when it is unfavourable (< –0.8) there are no excess monsoon seasons. If we consider the interannual variation of the monsoon since 1980 (Figure 1 b), consistent with the links of the monsoon with ENSO, the El Ninos of 1982 and 1987 were associated with droughts and the La Nina of 1988 with excess rainfall (Figure 4). It turned out that for 14 consecutive years beginning with 1988, there were no droughts; furthermore, during the strongest El Nino event of the century in 1997, the ISMR was higher than the long-term mean (Figure 1) and Krishna Kumar et al.[9] suggested that the relationship between the Indian monsoon and ENSO had weakened in the recent decades. Then came the drought of 2002, which occurred in association with a much weaker El Nino than that of 1997 and neither the statistical nor the dynamical models could predict it. The experience of 1997 and 2002 suggested that the link with ENSO had yet to be properly understood.

The intriguing monsoon seasons of 1997 and 2002 triggered studies which suggested a link to events over the equatorial Indian Ocean[10,11] and studies relating the impact of El Nino on the monsoon to the pattern of SST anomalies over the Pacific[12] and to the nature of the evolution of the El Nino in the seasons preceding the summer monsoon[13]. Gadgil et al.[10,11] showed that in addition to ENSO, the phase of the equatorial Indian Ocean Oscillation (EQUINOO), which is considered to be the atmospheric component of the Indian Ocean Dipole/Zonal Mode[14–18], makes a significant contribution to the interannual variation of ISMR. The results of Ihara et al.[19] of the association of ISMR with ENSO and EQUINOO over 1881–1998 are consistent with those of Gadgil et al.[11]. Gadgil et al.[11] further showed that there is a strong relationship between the extremes of ISMR and a composite index of ENSO and EQUINOO with all the droughts characterized by low values of this index and all excess monsoon seasons, high values. It is surprising that for a complex phenomenon such as the Indian monsoon, the extremes can be 'explained' in terms of links with just two modes: ENSO and EQUINOO.

In this article, we focus on the present understanding of the links of the interannual variation of ISMR to ENSO and EQUINOO and the major milestones leading to this understanding. We will not attempt a comprehensive review of the interannual variation of the monsoon which is also known to be related to several other factors[20] such as the Himalayan snow cover[21], Eurasian winter/spring snow-cover[22–27], pre-monsoon surface air temperature anomalies over India[28,29], the northern hemispheric temperature in winter[30], the surface air temperatures over northwest Europe and Eurasia[31], which may be caused by the different phases of the North Atlantic Oscillation[32]. These factors and ENSO and EQUINOO are not necessarily independent. For example, Fasullo[33] has shown that a strong association exists between ENSO and the Eurasian snow cover.

The Indian monsoon and its variability

The last three decades have witnessed enormous progress in our understanding of the physics of the monsoon and its variability. Over 300 years ago, Halley[34] suggested that the primary cause of the monsoon was the differential heating between ocean and land and the monsoon was considered to be a gigantic land–sea breeze. There is an alternative hypothesis in which the monsoon is considered as a manifestation of the seasonal migration of the intertropical convergence zone (ITCZ)[35], or the equatorial trough[36,37], in response to the seasonal variation of the latitude of maximum insolation. It is important to note that whereas the first hypothesis associates the monsoon with a system special to the monsoonal region, in the second, the system responsible is the planetary scale system associated with the major tropical rainbelt (ITCZ/equatorial trough) and the monsoonal regions differ only in the amplitude of the seasonal migration of the basic system. The two hypotheses have very different implications for the variability of the monsoon. For example, in the first case we expect the intensity of the monsoon to be directly related to the land–ocean temperature contrast.

Simpson[38] was perhaps the first to question the importance of the role played by land–ocean temperature contrast: 'It is only when one points out that India is much hotter in May before the monsoon sets in than in July when it is at its heights – or draws attention to the fact that the hottest part of India – the northwest gets no rain at all during the monsoon– or shows by statistics that the average temperature is much greater in years of bad rains than in years of good rains, that they begin to doubt whether they know the real cause of the monsoon.'

Subsequent studies have shown that the land surface temperature is higher when there is less rainfall during the summer monsoon and lower when the rainfall is higher[39]. This is shown in Figure 5 in which the patterns for the anomalies of rainfall and surface temperature for the drought monsoon season of 2002 are shown. Thus, rather than the land surface temperature determining the amount of rainfall via the impact on the difference between land and ocean temperature, the land temperature is determined by the rainfall (or lack thereof).

Sikka and Gadgil's[40] study of the daily satellite imagery over the Indian longitudes lent support to the second hypothesis considering the monsoon as a seasonal migration of the ITCZ. They showed that (i) the cloud band over the Indian subcontinent on an active monsoon day is strikingly similar to that characterizing the ITCZ over other parts of the tropics and (ii) dynamically the system has all the important characteristics of the ITCZ[35] including low
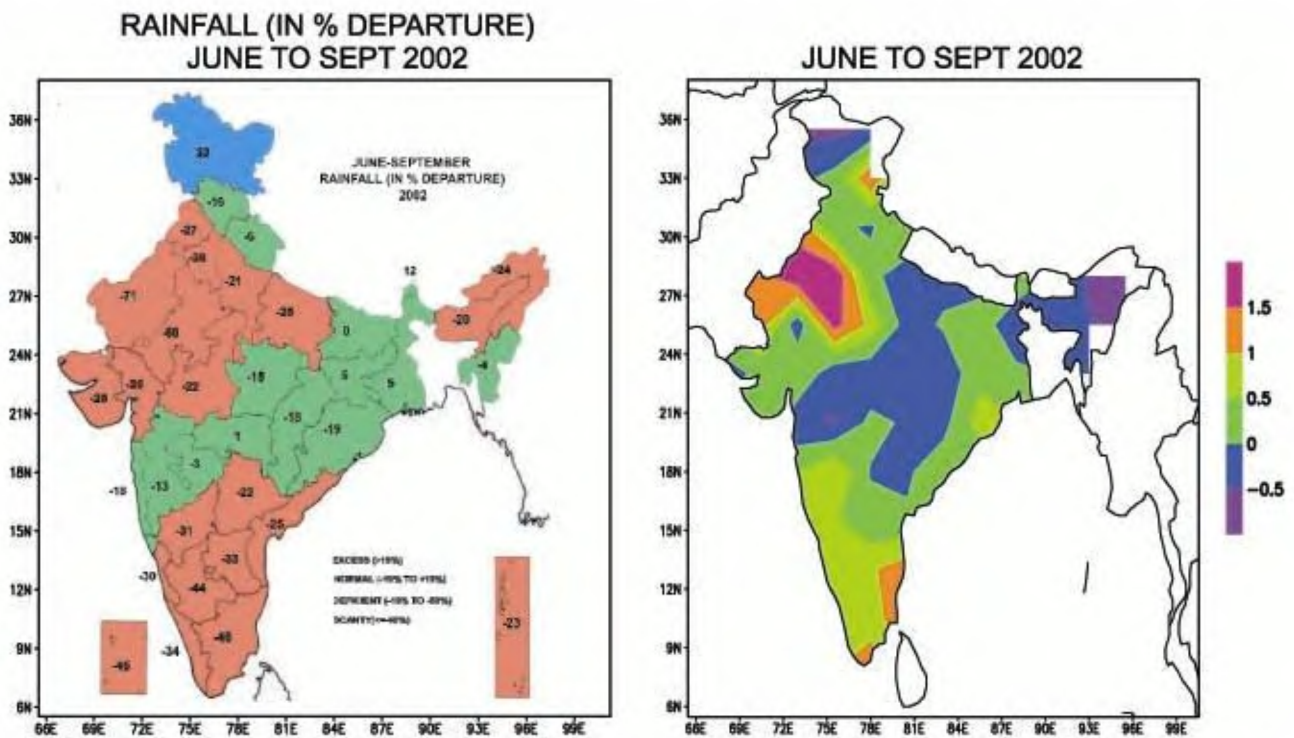
Figure 5. Anomalies of the rainfall (left) and maximum temperature (right) for the summer monsoon of 2002 (June to September).

level convergence, intense cyclonic vorticity above the boundary layer and organized deep convection. The large-scale rainfall over the Indian monsoon zone is directly related to the meridional shear of the zonal wind just above the boundary layer, i.e. the intensity of the continental ITCZ[41].

Thus, the monsoon is a manifestation of the seasonal migration of the ITCZ and monsoon variability is associated with the space–time variation of the continental ITCZ[42]. Important feedbacks, such as cloud radiation feedbacks or the feedback between vertical instability and mid-tropospheric heating by the deep clouds[43] will operate for the continental ITCZ as well as the oceanic ITCZ. In addition, processes special to the continental ITCZ such as land surface processes will play a role in determining the variability.

Sikka and Gadgil[40] have also pointed out two important features of the cloudbands over the Indian longitudes during the summer. First, there are two favourable locations for cloud bands/ITCZ, one over the heated subcontinent and another over the warm waters of the equatorial Indian Ocean. Since the convergence in both the zones cannot be intertropical, the term tropical convergence zone, TCZ (rather than the ITCZ) is used when referring to the Indian longitudes[44]. Second, there is a competition between the continental TCZ and the oceanic TCZ with active spells of one occurring primarily during weak spells of the other. In fact, a subsequent study[45] of active spells of the monsoon and intense dry spells, i.e. the so-called

breaks showed that the competition is particularly with the eastern equatorial Indian Ocean (Figure 6). A prominent feature of the intraseasonal variation is the northward propagations of the cloud bands from the equatorial Indian Ocean onto the Indian monsoon zone at intervals of 2–6 weeks (e.g. Figure 7) and the continental TCZ is maintained partly by these propagations of the oceanic TCZ. Thus the relationship between the TCZs is complex with the oceanic TCZ contributing to the maintenance of the continental TCZ on the one hand and competing with it on the other.

It has been known for a long time that a substantial fraction of the large scale rainfall over the Indian monsoon zone occurs in association with propagations of synoptic scale systems generated over the Bay of Bengal onto the Indian monsoon zone. Several of these systems are believed to arise from westward propagations of systems over the west Pacific[46]. Since a vast majority of the synoptic and planetary scale systems that result in rainfall over the monsoon zone are generated over the surrounding oceans, we expect the variation of the monsoon rainfall to be linked to that of organized deep convection over the surrounding oceans.

Satellite imagery clearly shows that the cloud band associated with the continental TCZ is often of planetary scale, stretching eastward from the Indian longitudes to over west and central Pacific and even beyond. The OLR pattern for the active/break composites based on the active/weak spells of the rainfall over the Indian monsoon
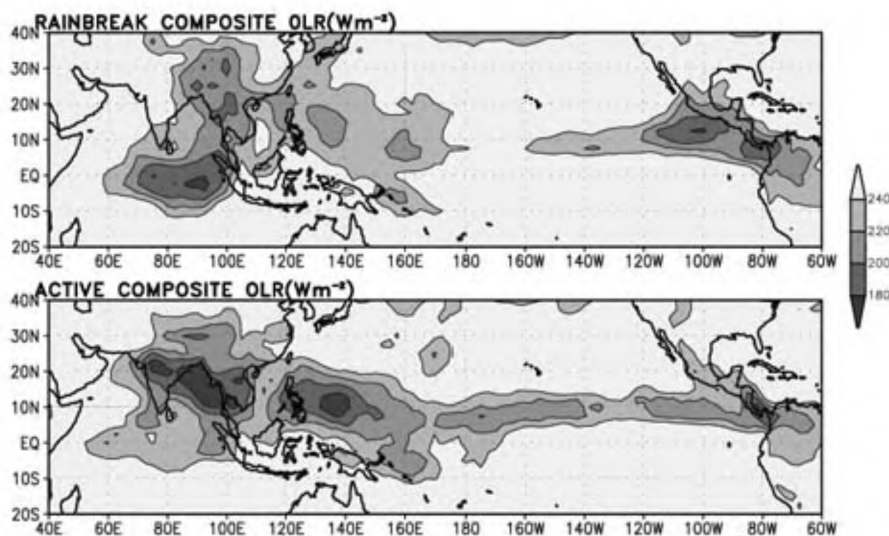
Figure 6. Composite OLR patterns for breaks in the rainfall over the Indian monsoon zone (top) and active rainspells over the Indian monsoon zone (bottom) (after Gadgil and Joseph[45]).
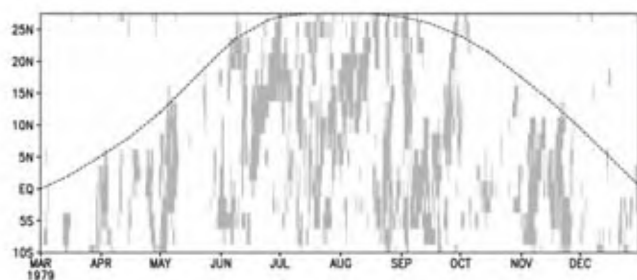

Figure 7. Variation of the region with deep clouds (identified as grids with OLR less than 200 and 180 Wm^{-2}) at 90°E during March–December 1979. The seasonal envelope is also indicated.
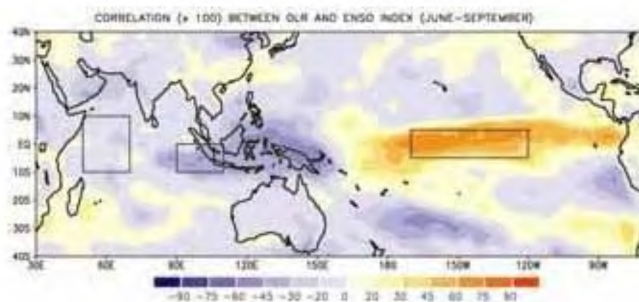

Figure 8. Correlation of June–September OLR with ENSO index.

zone, also shows the large longitudinal extent of the zone over which the variation of deep convective clouds is coherent (Figure 6). Thus, in addition to the links with the Indian Ocean, there appears to be a direct link between monsoon variability and the deep convection associated with the TCZ over the Pacific.

The major impact of El Nino (La Nina) over the Indian Ocean is the large positive (negative) OLR anomalies, suggesting suppression (enhancement) of deep convection over almost the entire equatorial and north Indian Ocean (Figure 8). This in turn appears to be associated with suppression (enhancement) over the Indian monsoon zone leading to the well-known association of droughts (excess rainfall seasons) with El Nino (La Nina). The relationship of convection anomalies over the Indian region with that over the Indian Ocean is not surprising since the large scale monsoon rainfall over the Indian region is associated with propagation of convective systems which are generated over the warm ocean around the subcontinent. We next consider the link of the monsoon with events over the equatorial Indian Ocean.

Monsoon, ENSO, EQUINOO and IOD

We can get an insight into the intriguing response of the monsoon to the El Ninos of 1997 and 2002 by considering the events over the equatorial Indian Ocean. We realized the importance of convection anomalies over the equatorial Indian Ocean in determining monsoon variability when we were examining the evolution of the monsoon of 2003 after the severe unanticipated drought[10,11] of 2002. The most striking feature of the monsoon of 2002, during a relatively weak El Nino, was the unprecedented deficit of 49% in the peak monsoon month of July. On the other hand, the July rainfall in 1997, with the intense El Nino over the Pacific, was only slightly below the long-term mean. Fortunately, the season of 2003 turned out to be far better than that of 2002, with that of ISMR being in excess of the mean by about 2% and the all-India rainfall in July 2003 in excess by about 7%. The OLR anomaly patterns for July 2002, 1997 and 2003 are shown in Figure 9. As expected, the OLR anomaly patterns over the Pacific are similar for the El Nino years of 1997, 2002

with the anomalies being of larger magnitude in 1997. The OLR anomaly patterns over the equatorial Indian Ocean are strikingly similar for 1997 and 2003, with suppression of convection over the eastern equatorial Indian Ocean and enhancement over the western equatorial Indian Ocean. On the other hand, the July 2002 pattern is characterized by suppression of convection over the western equatorial Indian Ocean and enhancement over the eastern equatorial Indian Ocean.

Suppression of convection over the eastern (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 the Indian Ocean Dipole/zonal mode (IOD/IODZM). Enhanced convection over the western part of the equatorial Indian Ocean and reduced convection over the eastern part are associated with easterly (i.e. from the east to the west) anomalies in the equatorial zonal wind; whereas the reverse case, i.e. with enhanced (suppressed) convection over the eastern (western) part, is associated with westerly anomalies of the zonal wind at the equator. The oscillation between these two states is the Equatorial Indian Ocean Oscillation. The patterns in Figure 9 suggest the presence of a positive phase of the EQUINOO in 1997, 2003 and a negative phase of the EQUINOO in 2002.

That a positive phase of EQUINOO with enhanced convection over WEIO is favourable for the monsoon is clearly seen from the pattern of the correlation of ISMR with OLR (Figure 3). It should be noted that the magnitude of the correlation with the convection over WEIO is comparable to that with the convection over the central Pacific corresponding to the link with ENSO. We use an index of the EQUINOO based on the anomaly of the zonal component of the surface wind at the equator (60°E–
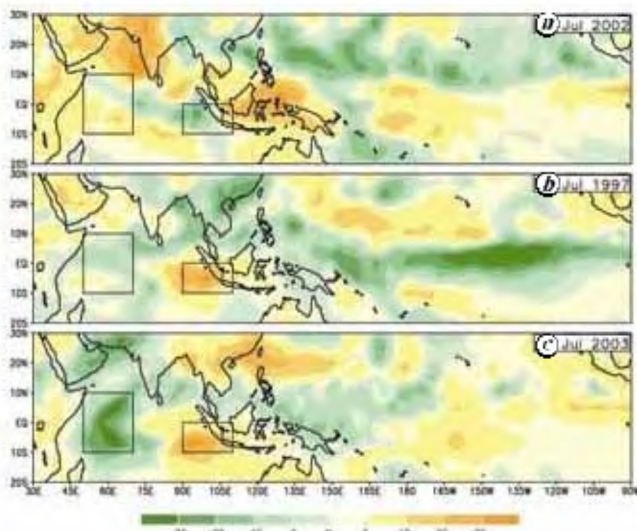

Figure 9. OLR anomaly patterns for (*a*) July 2002, (*b*) July1997 and (*c*) July 2003.
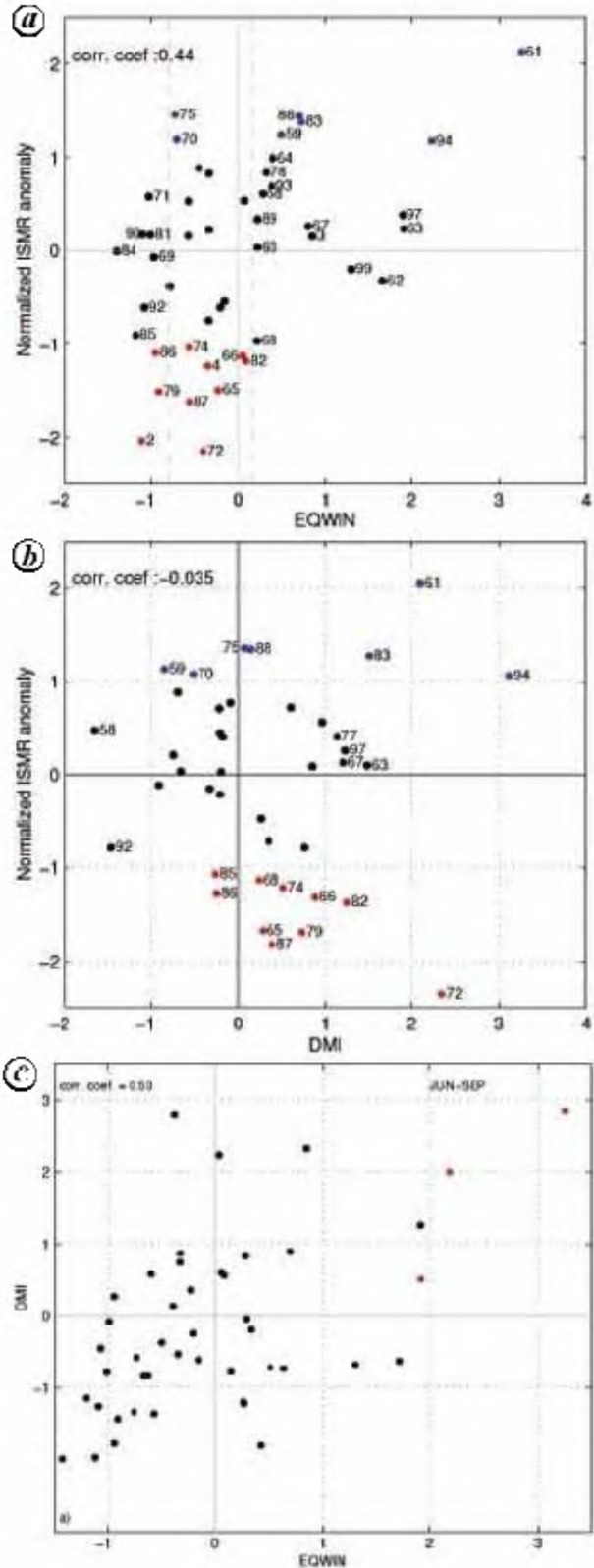

Figure 10. *a*, Normalized ISMR anomaly versus EQWIN for all the June–September seasons between 1958 and 2004. Red represents droughts, i.e. seasons with ISMR deficit greater than 1 standard deviation in magnitude; whereas blue represents excess monsoon seasons, i.e. with ISMR anomaly greater than 1 standard deviation. *b*, Same as (*a*) but versus DMI. *c*, DMI versus EQWIN.

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 so that positive values of EQWIN are favourable for the monsoon.

The relationship of ISMR with EQWIN is shown in Figure 10 *a*. It is seen that when EQUINOO is favourable (EQWIN is >0.2), there are no droughts and when it is unfavourable (EQWIN <–0.8) there are no excess monsoon seasons. The ISMR anomaly, the ENSO index and EQWIN for the summer monsoon seasons with the magnitude of the ISMR anomaly larger than one standard deviation (i.e. extremes) during 1979–2004 and the special season of 1997, are depicted in Figure 11 in order of increasing ISMR. It is seen that each drought (excess rainfall season) is associated with unfavourable (favourable) phases of either ENSO or EQUINOO, or both. In 1997, the two indices are comparable, but opposite in sign and the ISMR anomaly is small. In 1994, ENSO is unfavourable and the excess rainfall can be attributed to the favourable phase of EQUINOO. In the monsoon season of 2002, although the El Nino is weaker than that in 1997, 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 Nino or in the presence of a weak El Nino, but also excess rainfall seasons in which ENSO was unfavourable. The worst droughts are associated with unfavourable phases of both the modes.

In Figure 12 *a*, the ISMR for all the seasons, i.e. the June–September seasons in the period 1958–2004, is shown in the phase plane of the June to September averages of the ENSO index and EQWIN. The most striking feature of the distribution of extreme years is the clear separation between the years with excess and deficits with each of the surplus (deficit) years located above (below) a certain line in the phase plane (the line L in Figure 12 *a*). Furthermore, note that there are no seasons with even moderate deficits (between half and one standard deviation) above the line and only two seasons with moderate excess, below this line. This distribution in the phase plane suggests that an appropriate index would be a composite index, which is a linear combination of the
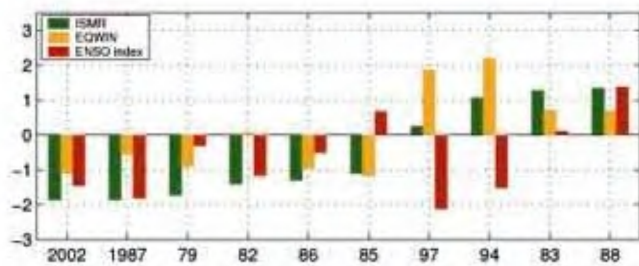
ENSO index and EQWIN. When the value of this index is high (i.e. point above the line L) not only is there no chance of droughts but also no chance of moderate deficits. For low values of the index (i.e. below the line L) there is no chance of excess rainfall seasons but a small chance of moderate excess rainfall. *It is important to note that the strong relationship between extremes of ISMR and this composite index is not predictive but simultaneous.* We find that there is a similar separation between extremes of the July–August rainfall in the phase plane of the concurrent values of the ENSO index and EQWIN (Figure 12 *b*).
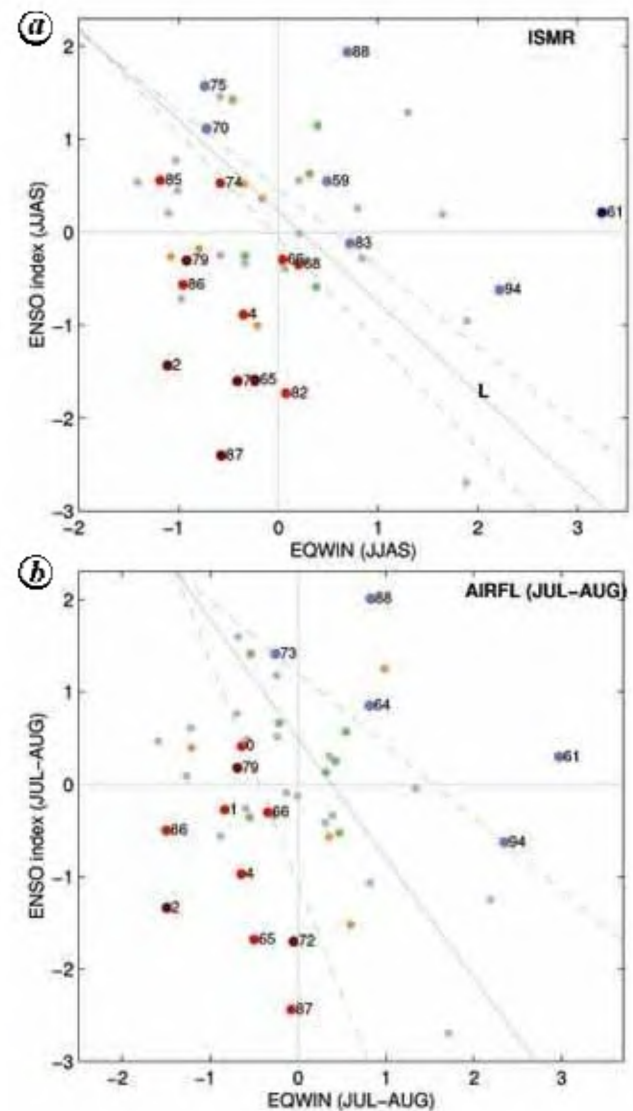

Figure 12. *a*, ISMR in the phase plane of June–September average values of the ENSO index and EQWIN for all the June–September seasons between 1958 and 2004. Red (dark red) represents seasons with ISMR deficit greater than 1 and 1.5 standard deviation respectively; whereas blue (dark blue) represents seasons with ISMR excess of magnitude greater than 1 and 1.5 standard deviation respectively. Green (orange) represents moderate positive (negative) ISMR anomaly of magnitude between 0.5 and 1 standard deviation. *b*, Same as (*a*) but for July–August all India rainfall.

Figure 11. The ISMR anomaly, EQWIN and ENSO index for all summer monsoon seasons with large deficit or excess during 1979–2002 and 1997.

The study of Ihara et al.[19] on the relationship of the variation of the monsoon with ENSO, EQUINOO and IOD, using data for a much longer period (from 1881 to 1998) than that used by Gadgil et al.[11] also suggests that the variation of ISMR is better described by use of indices of ENSO as well as EQWIN. For ENSO, they have used the Nino 3 index and for the IOD, the dipole mode index (DMI)[17] derived from the SST data of Kaplan et al.[47]. EQWIN was derived from the monthly zonal surface wind data from ICOADS[48]. For this longer dataset, the magnitude of the correlation between ISMR and Nino 3.4 index is somewhat larger (0.59), and that with EQWIN smaller (0.15). They have shown that, although EQWIN correlates poorly with ISMR, the linear reconstruction of ISMR on the basis of a multiple regression from the Nino 3 and this wind index better specifies the ISMR, than the regression with only Nino 3. They point out that their results regarding the equatorial wind anomalies are essentially consistent with those of Gadgil et al.[10,11], who analysed only the recent record. Hence they suggest that 'it is possible to conclude that the association between the Indian monsoon, equatorial zonal wind and the monsoon holds good for the entire observational record'.

EQUINOO has been considered to be the atmospheric component of coupled Indian Ocean dipole/zonal mode (IOD/IODZM). The oceanic component of the mode is characterized by anomalies of opposite sign in the sea surface temperature (SST) and sea surface height (SSH) over WEIO and EEIO. Generally, DMI, based on the difference in the SST anomalies of WEIO and EEIO[17], is used for identifying the phases of the IOD and its relationship with rainfall over different regions. Saji et al.[17] have shown that 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. The only statistically significant correlation is between DMI and September rainfall over India[49]. On the seasonal scale, the variation of ISMR does not appear to be related to that of DMI (Figure 10 b). Ihara et al.[19] also find 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.

EQUINOO has been considered to be the atmospheric component of IOD just as the southern oscillation is the atmospheric component of the coupled ENSO mode over the Pacific. However, whereas there is a tight linkage between the southern oscillation in the atmosphere and the fluctuations between El Nino and La Nina in the ocean, with the southern oscillation index being highly correlated to the different El Nino indices (correlation coefficient of 0.86 for the Nino 3.4 index), the correlation between EQWIN and DMI is only 0.52 for the period 1958–1997 (Figure 10 c). As expected, the positive dipole events of 1994 and 1997 were associated with a positive phase of EQUINOO. Thus, our attributing the excess rainfall in 1994 to favourable EQWIN is consistent with Behera et

al.'s[50] suggestion that the above normal ISMR during 1994 was due to the strong (positive) IOD event of that year. Annamalai and Liu[51] suggested that the combined effect of subsidence anomalies forced by intense El Nino events and the presence of IODZM results in the presence of negative precipitation anomalies over the entire longitudes of EEIO–maritime continent and this in turn leads to above normal rainfall over India during July–August. This is consistent with our attributing the normal monsoon of 1997 to the highly favourable EQWIN despite an unfavourable ENSO index. However, positive and negative phases of EQUINOO do not have a one-to-one relationship with positive and negative IOD events. For example, in 1962 and 1999 while the June–September average EQWIN was large and positive, DMI was negative; in 1972 while June–September average DMI was large and positive, EQWIN was negative. It is, therefore, not surprising that there is a substantive difference in the relationship of ISMR with EQWIN and that with DMI. It appears that what matters for ISMR is the atmospheric teleconnection with EQUINOO, while DMI does not play any role in the variability of ISMR. Thus, considering EQUINOO as the atmospheric component of the IOD may be neither correct nor useful.

Monsoon and ENSO: recent studies

In a recent study, Krishna Kumar (KK) et al.[12] suggested that El Nino events with the warmest SST anomalies in the central equatorial Pacific (such as 2002, Figure 13) are more effective in focusing drought-producing subsidence over India than events with the warmest SST over the eastern equatorial Pacific (such as 1997, Figure 13). This hypothesis is supported by the results of AGCM experiments forced with SST patterns resulting from linear combinations of the first two leading patterns of tropical Pacific SST variability. When the amplitude of the SST anomalies is sufficiently large, the second component, with positive SST anomalies over the central Pacific and negative over east Pacific, is shown to be associated with a large deficit in rainfall over the Indian region. However, there are major exceptions to this association. For example, a severe drought occurred in 1972, although the SST anomaly pattern of 1972 was similar to that of 1997 (Figure 13).

The results of the POGA experiments presented by KK yield some insights, which have not been discussed by them in the short paper. An important feature of the observed difference in the composite precipitation for El Ninos with severe droughts and drought-free El Nino years (Figure 14 a after their figure 2B) is the large negative anomaly over WEIO and the positive anomaly over EEIO. This pattern is consistent with the observed negative phase of EQUINOO in the severe drought associated with El Nino of 2002 and the observed positive phase of EQUINOO in the drought-free El Nino of 1997 (Figure
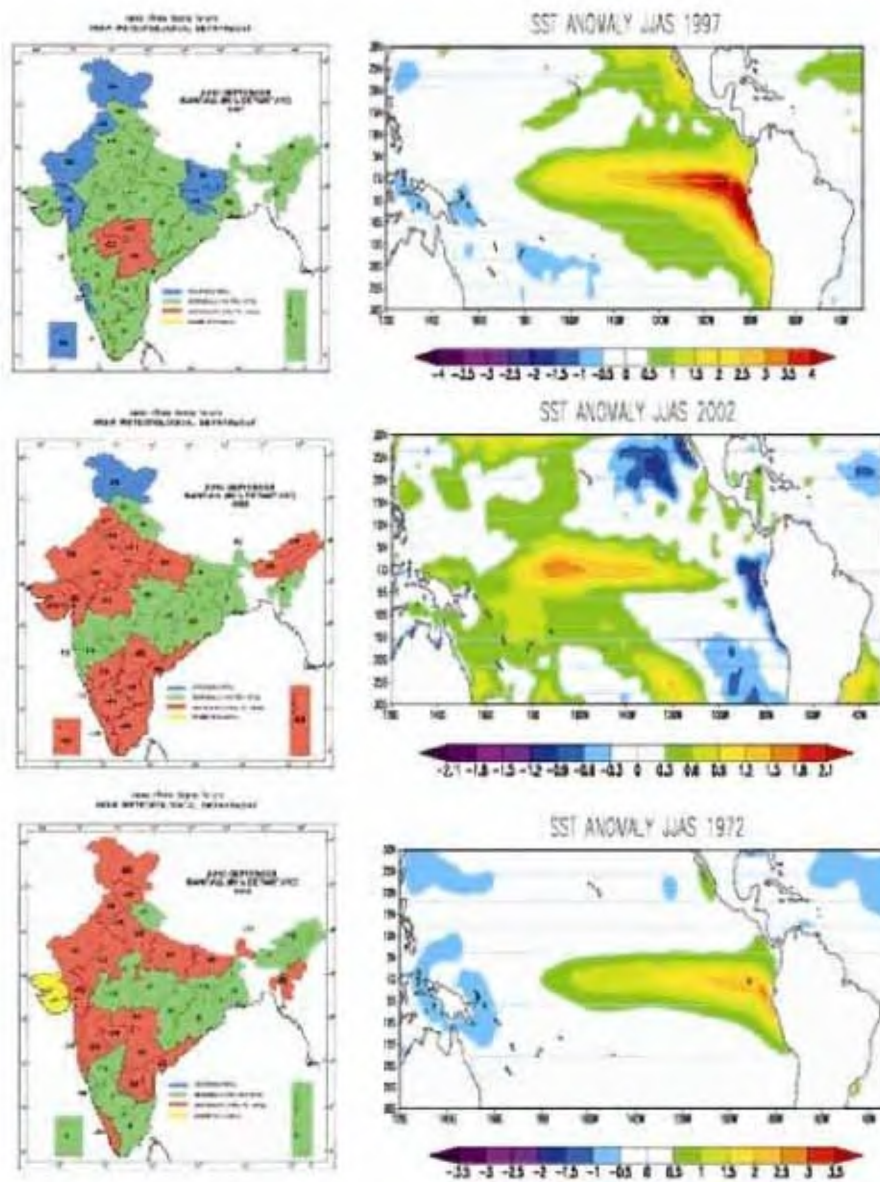
Figure 13. Indian summer monsoon rainfall anomalies (left) and Pacific SST anomalies (right) for 1997, 2002 and 1972.

9). However, the rainfall pattern for the difference in composite derived from idealized model experiments for impact of the second leading component of SST shown in Figure 14 *b* (after their figure 4B) indicates a zonal belt of negative anomalies over the equatorial Indian Ocean. It is interesting that east west gradients in precipitation over the equatorial Indian Ocean, similar to the observed, are seen in the difference between the composite rainfall patterns simulated for El Ninos with and without droughts from 16 member POGA runs of CCM3 for 1850–2004 (Figure 14 *c* after their figure S2, in the supporting online material), despite the specification of climatological SST for the Indian Ocean. The impact of El Nino on suppressing the convection over the equatorial

West Pacific and EEIO (Figure 8) is well known[52,53]. It has been suggested that suppression of convection over EEIO can trigger the development of positive EQUINOO and thereby positive IOD events[54,55]. It appears that in the 1850–2004 run of POGA simulation, in some El Nino cases, a positive phase of EQUINOO is indeed triggered. Thus the observed signature over the equatorial Indian Ocean is probably linked to the first mode since it is generated by the observed SST pattern of the Pacific, but not in the experiments with only the second SST mode over the Pacific. The result of KK that the second mode of SST is more effective in focusing drought-producing subsidence over India than the first can now be interpreted using our understanding of the association between

EQUINOO and ISMR. We expect that when the first mode dominates, a positive EQUINOO could be triggered and hence there is a chance of a drought-free El Nino; whereas when the second mode dominates, the El Nino will be associated with a drought since a positive EQUINOO will not be triggered. Whether this explanation is valid has to be assessed with analysis of the simulations.

KK *et al.* have also suggested that these findings have important implications for monsoon forecasting. In particular, the incorporation of additional information on the spatial distribution of SST anomalies over the equatorial Pacific Ocean in the statistical models is expected to improve monsoon forecast skill. However, Rajeevan and Pai[56] have shown that the incorporation of information on the spatial pattern of SST anomalies does not improve the association between El Nino and Indian monsoon rainfall and suggested that using the SST index over the central Pacific (Nino–3.4) may be a better indicator for the association than using the SST index over the east Pacific (Nino 3) or Trans Nino Index[57]. Whether other methods

of incorporating the information on spatial patterns of SST do lead to an improvement in prediction anticipated by KK needs to be investigated.

In an interesting study of the El Nino–monsoon relationship, Ihara *et al.*[13] have demonstrated the critical role played by the nature of the evolution of the El Nino in the seasons preceding the summer monsoon. They have shown that when the ISMR is not deficit despite the co-occurrence of an El Nino event, warming over the eastern Pacific starts from boreal winter and persists through the reference summer; whereas when El Nino–deficit ISMR relationship holds, the eastern equatorial Pacific starts warming rapidly only about a season before the reference summer so that western central Pacific remains cold during the summer monsoon season. The aim of this study was to identify a robust feature of Indo-Pacific SST evolutions associated with wet monsoon during El Nino events over the long period of over hundred years. The implications of this interesting result for prediction of the impact of an evolving El Nino on the monsoon needs to be further explored.
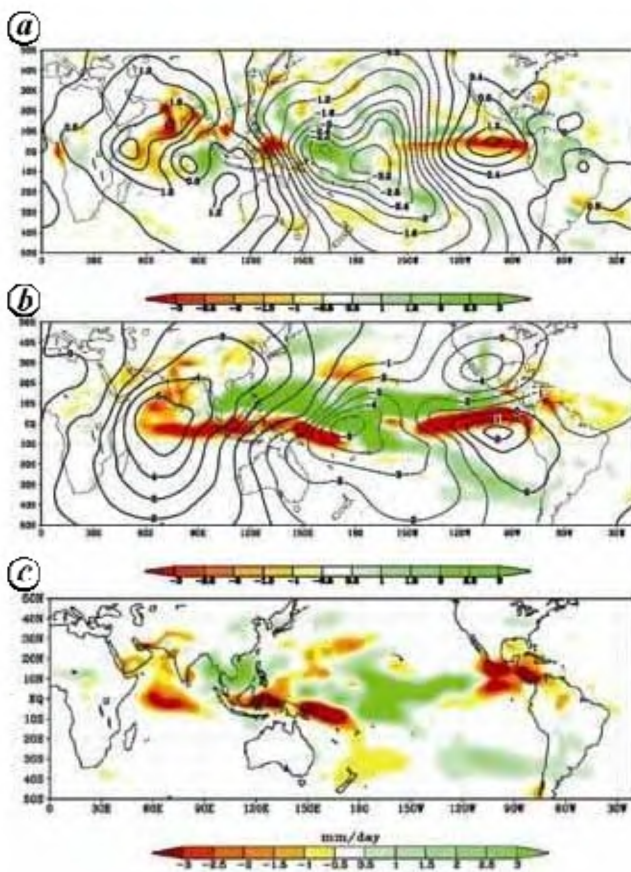
Simulation of interannual variation with atmospheric models

Given the links between the Indian monsoon and ENSO, it was expected that it would be possible to simulate the interannual variation of the ISMR with AGCMs when the observed SSTs are specified as a boundary condition. However, the results of several such studies[58,59] suggest that the problem remains a challenging one. Analysis of the simulations for the years 1979–95 by 20 state-of-the-art AGCMs organized under the Atmospheric Model Intercomparison Project (AMIP, Gates[60]) showed that while almost all models simulated the correct sign of the ISMR anomaly in 1988, a vast majority of the models failed to capture the anomaly for the excess monsoon season of 1994 (during which the ENSO was unfavourable)[2]. None of the models participating in the CLIVAR/Monsoon GCM Intercomparison Project, could simulate realistically the observed response of the Indian monsoon to the 1997 El Nino event[61,62]. Wang *et al.*[62] suggest that the models experience unusual difficulties in simulating the Indian monsoon of 1997.

Thus, the skill of the models in simulating the sign of the anomalies is not the same for all the droughts or excess rainfall years. On the whole, the skill of the models in simulating the sign of the anomaly for extreme ISMR seasons is higher for the extreme seasons which are associated with ENSO. The poor skill for the seasons of 1994 and 1997 which had a strong positive phase of EQUINOO (Figure 11) suggests that more research and development effort is required to develop models which are capable of a realistic simulation of the links of the monsoon to EQUINOO.

Figure 14. *a*, Observed composite difference pattern between severe drought and drought-free years of velocity potential (contours) and rainfall (shaded) (figure 2B from KK). *b*, The ensemble mean rainfall (shading) and 200 hPa velocity potential (contour) differences between experiments (ii) and (iii) (figure 4B from KK). *c*, Composite rainfall difference map between severe drought and drought-free years of the POGA simulations. (Figure S2 from KK.)

Prediction

Predicting the Indian summer monsoon rainfall is one of the important mandates of the India Meteorological Department. Hence until the skill of the atmospheric and coupled models in simulating and predicting the interannual variation of the Indian monsoon improves, the empirical approach has to be adopted for operational forecasts. However, our analysis of the predictions generated by the empirical models used operationally by IMD since 1932, suggests that the performance of these models based on the relationship of the monsoon rainfall to atmospheric/oceanic conditions over different parts of the globe has not been satisfactory[2]. Whether new approaches[63–64] which take into account the inherent nonlinearity in the relationships will yield better results, has to be explored.

The predictors in these models are primarily related to the link of the monsoon with ENSO. A recent study[13] has suggested that the El Nino–monsoon relationship depends on the nature of the evolution of El Nino in the seasons prior to the summer monsoon. They have shown that when warming over the eastern Pacific starts from boreal winter and persists through the reference summer, the ISMR is not deficit despite the co-occurrence of an El Nino event, whereas when El Nino–deficit ISMR relationship holds, the eastern equatorial Pacific starts warming rapidly only about a season before the reference summer. It would be worthwhile to explore use of this relationship in empirical models of prediction.

Our experience of the monsoon of 2006 suggests that incorporation of predictors associated with EQUINOO along with those associated with ENSO may improve predictions. Based on the analysis of predictors, IMD issued a long-range forecast for the 2006 monsoon season rainfall as 93% of long period average. This inference of below normal was drawn based primarily on warm water anomalies over the equatorial Pacific[65] and the warming

tendency of SST anomalies over the equatorial Pacific (Nino 3.4). The monsoon rainfall performance, in fact, was alarming till the third week of July. As on 26 July 2006, all-India cumulative rainfall departure was 13% below normal. However, rainfall activity revived by the third week of July and good rainfall activity extended almost unabated till the middle of September, thus improving the rainfall situation over the country. At the end of monsoon season, seasonal rainfall was 100% of its long period average[66]. During August–September there were large positive (negative) OLR anomalies over the eastern (western) equatorial Indian Ocean (Figure 15) and anomalous easterlies over the equatorial Indian Ocean,
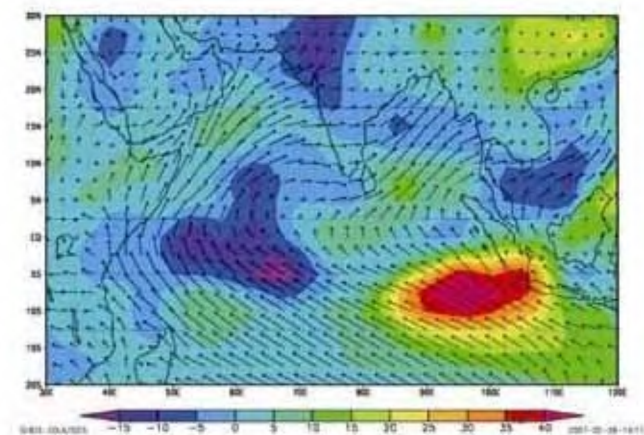

Figure 15. OLR (shaded) and surface wind anomalies during August–September 2006.
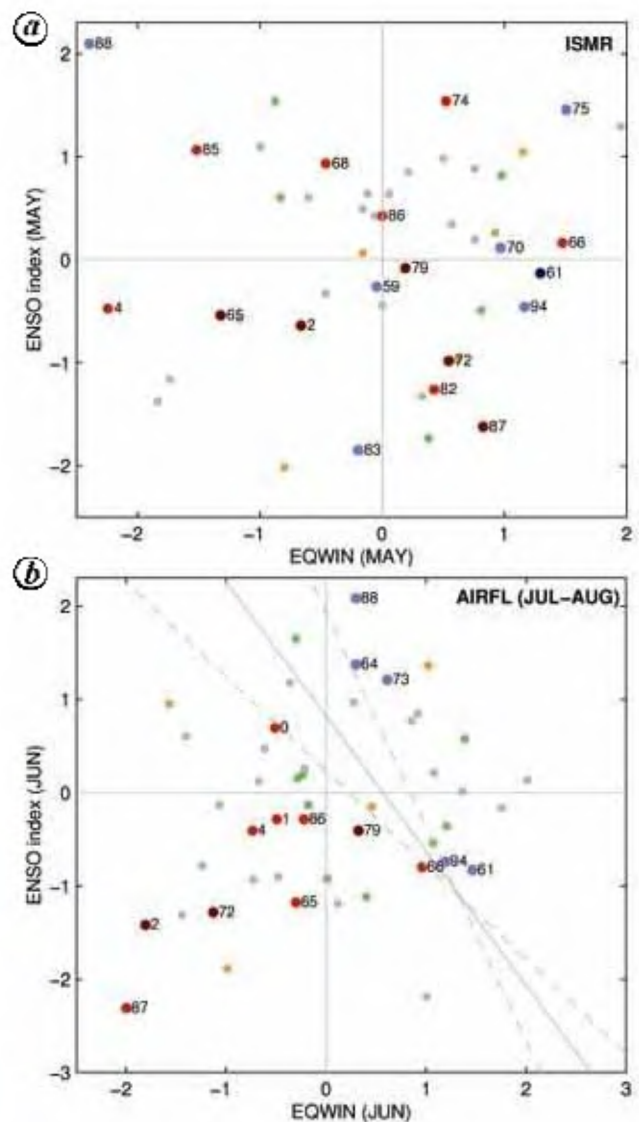

Figure 16. *a*, Same as Figure 12 *a* but for ISMR in the phase plane of May values of the ENSO index and EQWIN for all the June–September seasons between 1958 and 2004. *b*, Same as Figure 12 *b* but for July–August all India rainfall in the phase plane of June values of ENSO index and EQWIN for all the July–August seasons between 1958 and 2004.

suggesting that a positive phase of EQUINOO had developed in this period. The enhanced rainfall during the second half of monsoon season could be attributed to this as the characteristic link of enhanced convection from the west Indian Ocean to north west coast of India and adjoining North-east Arabian Sea is also seen in Figure 15. Clearly, had the development of positive EQUINOO phase by August been predicted, it might have been possible to predict that the deficit would certainly not be as large as expected from ENSO alone.

We explored the possibility of using EQWIN and ENSO indices before the season for prediction about the forthcoming season. However, there appears to be relatively little information about the rainfall for the forthcoming season in the May values of EQWIN and ENSO index (Figure 16 a). Preliminary results of analysis of rainfall over India, EQWIN and ENSO indices suggest that like in the case of association, i.e. concurrent values of indices, the extremes of the mid-season rainfall (July and August) are well separated in the phase plane of the indices for June (Figure 16 b). So from the June indices, it is possible to derive useful information about nonoccurrence of extremes (either deficit or excess rainfall) for July and August together. More studies are required to assess whether it is possible to predict the EQUINOO for any part of the season (with statistical models) and also the impact on the Indian rainfall in that part of the season for a given (predicted) ENSO state.

Clearly it is important to embark on detailed studies of the physics of EQUINOO with new observations over critical regions as well as modelling studies. This could lead to empirical models for prediction of EQUINOO. We have seen that most atmospheric models are able to capture the extremes of ISMR when they are linked to ENSO. This was achieved by concerted efforts under an international programme 'MONEG' in the nineties under which the cases of 1987 and 1988 were studied with a slew of models. We now need research and development of atmospheric and coupled models to a level at which they can simulate realistically the response of the Indian monsoon to EQUINOO as well as ENSO. Once this is achieved it may be possible to generate reasonable predictions of the Indian summer monsoon rainfall with dynamical models.

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A promising alternative to prediction of seasonal mean all India rainfall

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Prediction of seasonal mean All India Rainfall (AIR) is useful during extreme monsoon years (droughts and floods) when the rainfall anomaly is homogeneous over the country. It is, however, useless for any regional hydro-meteorological applications during 'normal' monsoon years (70 per cent of available record), when the rainfall anomaly is quite inhomogeneous within the country. Further, there exists an intrinsic limit to predict the seasonal mean monsoon. The theoretically achievable skill (with perfect model and near perfect data) for seasonal prediction of rainfall being barely useful, there is a need to explore an alternative strategy for monsoon prediction even if it is with a shorter lead time. Based on some of our previous work, we propose here that predicting the phases of the monsoon sub-seasonal oscillation (active and break spells) 3–4 weeks in advance is such an alternative strategy. We argue that such predictions would be more useful for regional hydro-meteorological applications. Potential for such extended range prediction is demonstrated. Using an empirical model, it is further demonstrated that this potential can be achieved and useful prediction of monsoon breaks three weeks in advance could be made. Future direction in improving such extended range prediction of sub-seasonal spells is discussed.

Keywords: All India rainfall, atmospheric general circulation model, seasonal mean.

The need and scope of prediction of seasonal mean monsoon rainfall

LARGE scale droughts and floods of the Indian summer monsoon (ISM) adversely affect country's agricultural production and economy and also cause immense property damage and human loss. Forewarning of seasonal mean rainfall is, therefore, demanded by the country's policy makers. As a result, for over a century, attempts have been made to predict the total summer monsoon rainfall using empirical techniques involving local and global antecedant parameters that correlate with the monsoon rainfall[1–6]. The linear and nonlinear regression models as well as the neural network-based models[7] perform reasonably well

when the monsoon is close to normal but fails to predict the extremes with useful skill. A case in point is the failure of almost all empirical models in predicting the drought[8] of 2002. Another intrinsic limitation of the empirical techniques arises from interdecadal variation of the correlations between predictors and monsoon rainfall[9–11]. Dynamical prediction of the seasonal mean monsoon using state-of-the-art climate models, therefore, offers a logical alternative to empirical forecasting. Unfortunately, the skill of prediction of the summer precipitation over the Asian monsoon region is currently negligible for almost all state-of-the-art atmospheric general circulation models (AGCM)[12–16]. Multi-model super-ensemble forecasting[17–20] shows some promise of improving the dynamical forecasts beyond the skill of individual models. However, the skill of such models also remains in the sub-useful range.

Reasons for AGCMs inability to predict the seasonal mean Indian monsoon rainfall

The inability of the state-of-the-art AGCMs in predicting the seasonal mean monsoon appears to be due to the following major factors.

First, even though AGCMs have improved over the last three decades in simulating the global climate in general, most models still have major systematic bias in simulating the seasonal mean ISM precipitation and its interannual variability (IAV)[21–25]. Charney and Shukla[26] suggested that low frequency boundary forcing such as the tropical sea surface temperature (SST) variations predisposes the monsoon system toward a dry or a wet state. In other words, anomalous boundary conditions may provide potential predictability. For this to be true, models should be able to capture the interannual variability of the ISM. However, in reality, this is not the case as most models find the simulation of even the mean summer monsoon precipitation extremely difficult and have even greater difficulty in simulating the interannual variability of the ISM rainfall.

The predictable component of IAV of Indian summer monsoon comes from the teleconnection of Indian monsoon with slowly varying 'external' forcing such as the El Nino and Southern Oscillation (ENSO)[27]. Simulation of the correct sign and amplitude of IAV of the monsoon by the AGCM depends on its ability to correctly simulate