

A common spatial mode for intra-seasonal and inter-annual variation and predictability of the Indian summer monsoon

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How and to what extent the intra-seasonal oscillations (ISOs) of the Indian summer monsoon influence the seasonal mean and its inter-annual variability is investigated using long records of daily circulation data (1956–1997) and outgoing long wave radiation (OLR) data (1974–1997). The underlying spatial structure of a typical ISO cycle that is invariant from event to event and year to year is brought out. It is shown that the intra-seasonal and inter-annual variations are governed by a common mode of spatial variability. A higher frequency of occurrence of ‘active’ (‘break’) conditions within a monsoon season, therefore, could result in a ‘strong’ (‘weak’) summer monsoon. Two-dimensional probability density function estimates of the ISOs show that ‘strong’ (‘weak’) monsoon years are indeed associated with higher probability of occurrence of ‘active’ (‘break’) conditions. For the first time, these results show that the frequency of chaotic ISO regimes determine the seasonal mean monsoon, thereby setting a limit on monsoon predictability.

WHILE conceptual basis for predicting the tropical climate in general has been established¹, the prediction of the Indian summer monsoon variability remains

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elusive². The predictability of the Indian summer monsoon depends on whether the inter-annual summer monsoon variability is dominated by the slowly varying external forcing or by internal processes. What may be responsible for generating low frequency (LF) internal variation in the monsoon region? The intra-seasonal oscillations (ISOs) of the Indian monsoon that manifest in the form of vigorous ‘active’ and ‘break’ spells of the monsoon within the summer season are known to be primarily driven by internal dynamics^{3,4}. If the ISOs could influence the seasonal mean significantly, they could give rise to internal LF variation of the monsoon. Goswami⁵ proposed a conceptual framework and indicated that the ISOs can, in principle, influence the seasonal mean monsoon significantly.

The conceptual model is outlined below. June to September (JJAS) mean monsoon precipitation has a primary zone of maximum precipitation from north Bay of Bengal extending westward through the Gangetic Valley (known as monsoon trough) and a secondary maximum south of the equator (between 0 and 10°S) over the warm waters of the Indian Ocean (Figure 1). The two maxima in seasonal mean precipitation represent two favourable locations of the tropical convergence zone (TCZ). The fluctuations of the TCZ between the two locations and repeated northward propagation from the southern to the northern position of the TCZ result in the ISOs. The phase of the ISO when the TCZ is in the northern (southern) position corresponds to the ‘active’ (‘break’) monsoon condition. If the intra-seasonal anomalies associated with the ‘active’ (‘break’) condition enhance (weaken) the large-scale monsoon flow, a larger frequency of ‘active’ (‘break’) conditions could result in a stronger (weaker) than normal seasonal mean monsoon. The ISOs are characterized by a broad-band spectrum with period between 10 and 90 days and are not pure sinusoidal oscillations. Hence the duration of ‘active’ and ‘break’ conditions during a monsoon season could be different. Moreover, since these are low frequency oscillations, the number of ‘active’ and ‘break’ episodes in a monsoon season could also be unequal due to their initial phases.

The underlying requirement in these arguments is that the ISOs and inter-annual variability of the Indian summer monsoon must be governed by a common mode of spatial variability. While a large volume of literature exists on study of spatial and temporal character of the basic monsoonal ISOs, only few studies have addressed the question of relationship between the ISOs and inter-annual variability of the Indian summer monsoon. Ferranti *et al.*⁶ showed that the intra-seasonal and inter-annual variability simulated by a general circulation model (GCM) are very similar. However, due to systematic errors in simulating the mean monsoon by the GCM, it is unclear whether the results could be applied directly to the real monsoon system. Goswami *et al.*⁷ used daily observations of surface wind for 10 years and showed that the spatial structure of the intra-seasonal and inter-annual variability are similar. Annamalai *et al.*⁸ used NCEP/NCAR and ECMWF reanalysis for 17 years (1979–1995) but could not find a common mode of variability that describes intra-seasonal and inter-annual variability of the monsoon. Palmer⁹ introduced the concept of ‘nudged chaos’ where the ISOs could be intrinsically ‘chaotic’, but the slowly varying forcing could ‘nudge’ them to reside in either one of the two possible equilibria for a long enough time and thereby influence the seasonal mean. Annamalai *et al.*⁸ also examined whether the statistics of the ISOs are modulated by the slowly varying boundary forcing (El Ninos and La Ninas). However, due to the small sample size

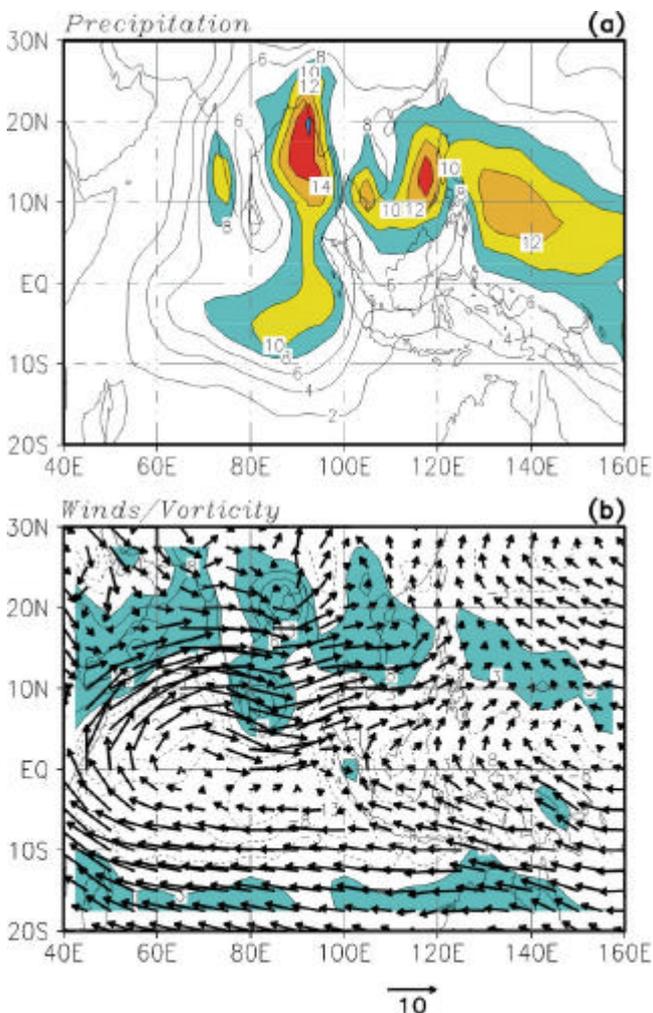


Figure 1. *a*, Long-term mean observed precipitation (mm day^{-1}) during the summer monsoon season (June–September, JJAS). Contours greater than 8 mm day^{-1} are shaded; *b*, Same as *a*, but for vector winds (ms^{-1}) at 850 hPa during JJAS (arrows) and corresponding relative vorticity (contours, $1.0 \times 10^{-6} \text{ s}^{-1}$). Positive (negative) contours are solid (dashed) lines. Zero contour is not plotted and positive vorticity contours greater than 3 units are shaded.

(number of El Ninos and La Ninas within that period), the statistical significance of their results remains unclear. Thus, all studies using observation so far failed to establish a clear relationship between the ISOs and inter-annual variation of the Indian summer monsoon. One reason for obtaining often contradictory results by some of the previous studies is due to the rather small length of observations used in many of these studies. Moreover, most previous studies did not take enough care to separate the contribution of the ISOs to the seasonal mean from that arising from 'external' forcing. In order to highlight the role of the ISOs, it is important to separate the contribution of the ISOs to the seasonal mean from that coming from the external forcing.

In the present study, we use 42 years daily data and propose a method to separate the contribution of the ISOs to the seasonal mean, from that of the external forcing. We show that the intra-seasonal and inter-annual monsoon variability are indeed governed by a common mode of spatial variability. We further show that the ISOs make dominating contribution to the inter-annual variability, thereby setting a limit on summer monsoon predictability.

The data used in this study are the daily winds at a number of vertical levels from the NCEP/NCAR re-analysis project¹⁰ during the period from 1956 to 1997. For convection, we used satellite derived outgoing long wave radiation (OLR)¹¹. For identifying the strength of the Indian summer monsoon, the all India monsoon rainfall (IMR) index¹² has been used.

The objective of the present study is to isolate the component of the seasonal mean that is contributed by the ISOs. A part of the seasonal mean is forced by external forcing such as the El Nino and Southern Oscillation. The slowly varying external forcing may result in variations of the annual cycle from year to year. To bring out the fundamental role of the ISOs, it is important to separate the ISO forced component of the seasonal mean from the externally forced component. This is achieved by calculating daily anomalies in a given year with respect to the annual cycle (sum of annual and semi-annual harmonics) of that year. In this manner, inter-annual variations of the annual cycle are eliminated. Power spectral estimate of various fields indicates two prominent bands of periods, one between 30 and 60 days and another between 10 and 20 days. To study the detailed structure of these two types of oscillations, Butterworth bandpass filters are used with peak response at the observed peak in these bands. A circulation-based criterion to define the 'active', 'break' and other phases of the ISOs has been evolved. Filtered zonal winds at 850 hPa at a reference point in the north Bay of Bengal (90°E, 15°N) are used with peaks and troughs of the filtered zonal winds representing 'active' and 'break' conditions, respectively. In a given year, the 'active' ('break') days are those for which the zonal

wind anomalies at the reference point are greater (lesser) than the + 1 SD (-1 SD). It has been seen that a small shift of the reference point does not significantly affect the definition of 'active' and 'break' days. It is found that the composite of daily precipitation during 'active' ('break') days defined this way corresponds closely to the canonical pattern of daily rainfall variability associated with typical 'active' and 'break' condition of the Indian monsoon.

The underlying spatial patterns of the dominant ISOs that are invariant from event to event and from year to year are constructed using a compositing technique¹³. A period of 20 years (1978–1997) is sufficient to bring out the common pattern. All 'active' ('break') days associated with the 30 to 60 day filtered winds between 1 June and 30 September for all 20 years are identified. Average winds and outgoing long wave radiation (OLR) constructed from all 'active' and 'break' days are shown in Figure 2. The significant coherent large-scale wind and OLR anomalies that emerge even after averaging over eighty 'active' ('break') episodes (20 years), show that all 'active' ('break') phases possess underlying common spatial pattern of variability. A comparison of Figures 1 and 2 shows that a typical 'active' ('break') condition is associated with strengthening (weakening) of the seasonal mean low-level monsoon circulation, enhancing (weakening) the cyclonic vorticity and convective activity in the northern position of the TCZ (monsoon trough) and weakening (enhancing) the convection in the southern position of the TCZ. The typical evolution of the 30 to 60 day mode constructed by creating a composite of eight different phases of the oscillation (figure not shown) shows that the ISO is characterized by a systematic northward propagation of the TCZ from the southern to northern position. Similar phase composites for the 10 to 20 day mode are also constructed. It is seen that (figure not shown) that the 10 to 20 day mode is rather regional in character with its significant anomalies mainly confined in the Bay of Bengal.

After studying the structure of the 30 to 60 day and 10 to 20 day modes separately, the total ISO activity is defined by fields filtered with a bandpass filter with peak response at 35 days and half response at 15 days and 80 days, respectively, for all years. In Figure 3, the dominant Empirical Orthogonal Function (EOF) of ISO variability of 850 hPa wind between 1 June and 30 September for the 20-year period (1978–1997) is compared to the dominant inter-annual EOF of the seasonal mean wind during a 40-year period (1958–1997). From the correlation between the projection coefficient (PC) of the inter-annual EOF1 and IMR ($r = 0.62$), it is seen that the inter-annual EOF1 represents the dominant inter-annual variation of the Indian summer monsoon. Similarity between both the patterns establishes the fact that the dominant ISO and inter-annual variations of the Indian monsoon are governed by a common mode of

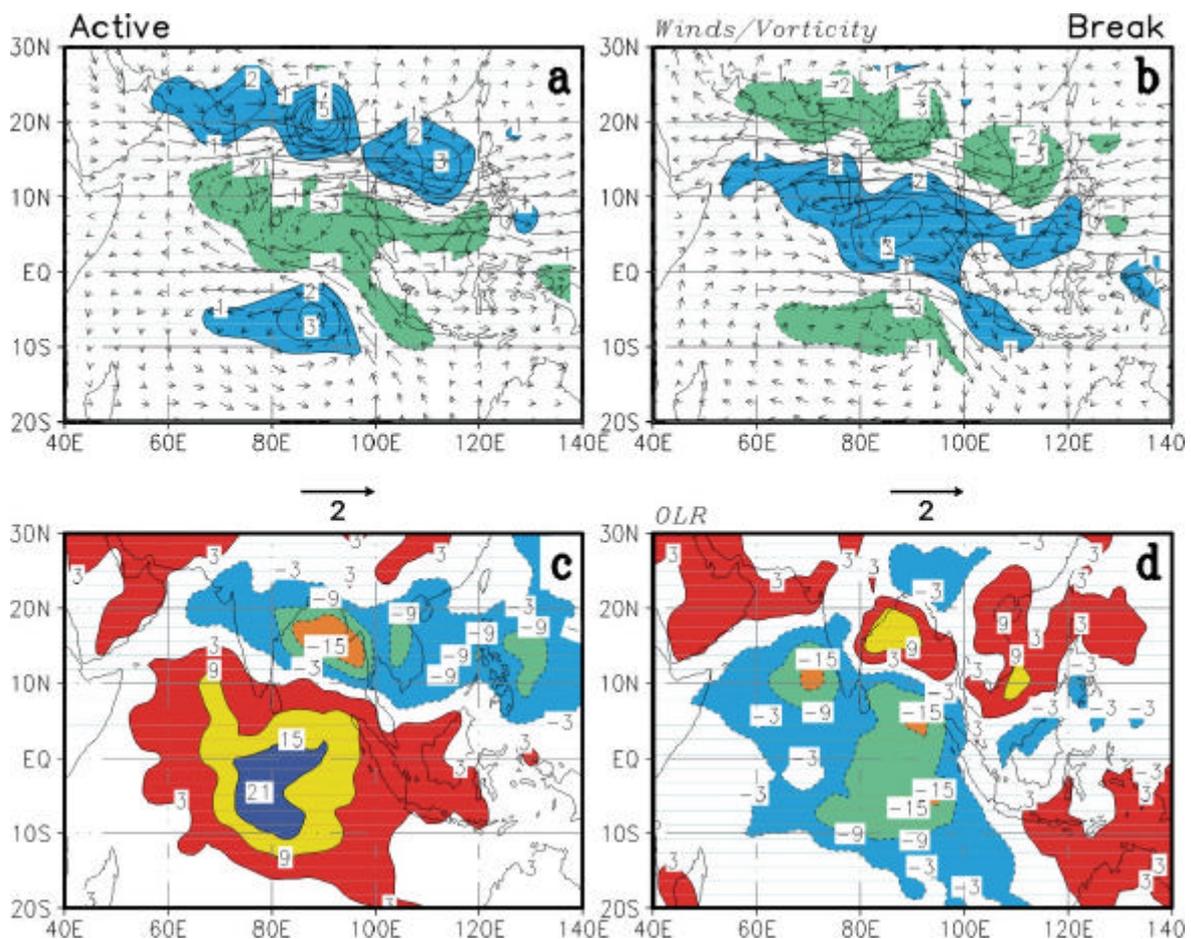


Figure 2. Circulation and convection anomalies representing extreme phases of the ISOs. *a*, Mean composite vector wind anomalies (arrows, ms^{-1} at 850 hPa, and associated relative vorticity (contours, $1.0 \times 10^{-6} \text{ s}^{-1}$) based on all 'active' conditions during the 20-year period (1978–1997); *b*, Same as *a*, based on all 'break' conditions; *c*, Corresponding mean composite OLR anomalies (Wm^{-2}) based on all 'active' conditions; *d*, Same as *c* but based on all 'break' conditions.

spatial variability. It is seen (figure not shown) that the spatial pattern of SD of the ISO-filtered low-level relative vorticity is also quite similar to that of seasonal mean vorticity. These observations support the conclusion that the patterns of intra-seasonal and inter-annual variability are similar.

Having established that spatial patterns of intra-seasonal and inter-annual variability are similar, we test whether 'strong' ('weak') monsoon years are characterized by higher frequency of occurrence of 'active' ('break') conditions. For this purpose, probability density function (PDF) estimates for the ISOs are made. Seven 'strong' (1956, 1959, 1961, 1970, 1975, 1983, 1988) and ten 'weak' (1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987) monsoon years are defined objectively by using a criterion $\text{IMR} > 1.0 \text{ SD}$ and $\text{IMR} < -1.0 \text{ SD}$, respectively. An EOF analysis of ISO filtered vorticity at 850 hPa for 'strong' ('weak') years

between 1 June and 30 September is carried out. The probability density function (PDF) of the PCs in the reduced phase space defined by the first two EOFs in each case is obtained using a Gaussian kernel estimator¹⁴ and a smoothing parameter large enough to detect multimodality with statistical significance. Both the PCs are normalized by their own temporal SD. The PDFs of the 'strong' and 'weak' years are shown in Figure 4. To test the statistical significance of these maxima, we created 1000 random sets of time series having the same variance and autocorrelation at 1-day lag equal to those of observed PC1 and PC2 and 2D PDFs were calculated for each of them. In Figure 4 shading represents regions where the observed PDF is significantly greater than the random ones with 90% confidence. For 'strong' and 'weak' years, the PDF of the ISO activity is clearly non-Gaussian. The spatial pattern which corresponds to the maxima of PDF in each case is constructed using appropriate normaliza-

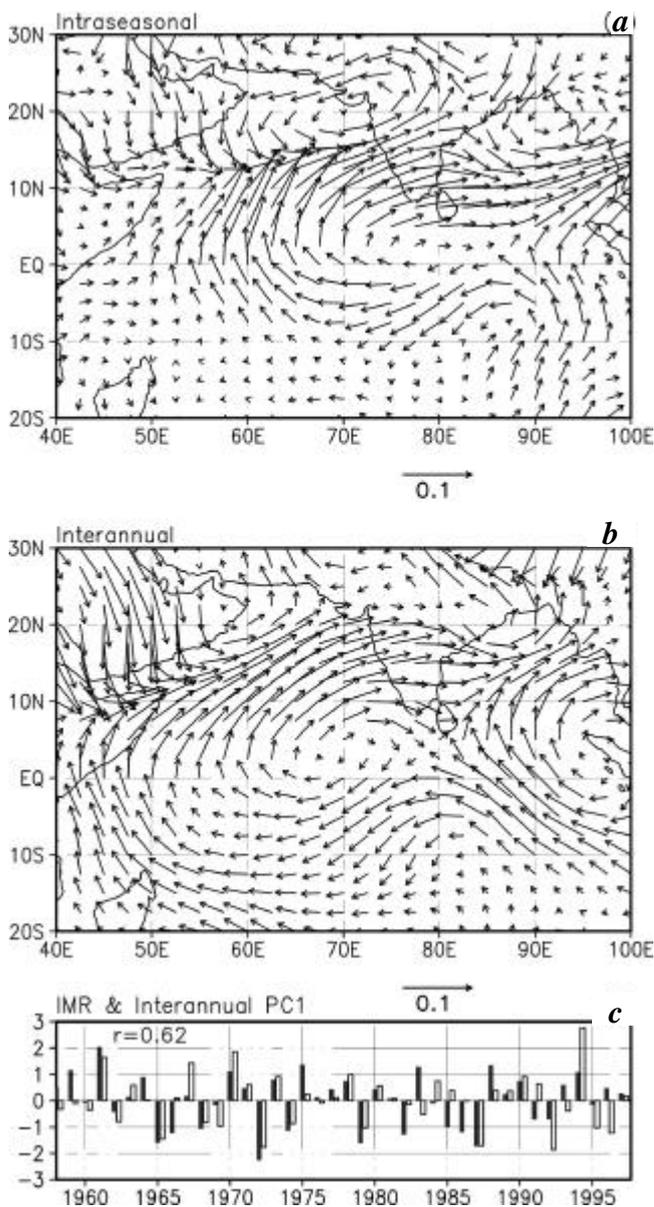


Figure 3. *a*, First Empirical Orthogonal Function (EOF) of the ISO filtered 850 hPa winds; *b*, First inter-annual EOF of JJAS mean winds at 850 hPa. Units of vector loadings are arbitrary; *c*, Normalized IMR (filled bars) and inter-annual first principal component (PC1, unfilled bars).

tion constants and corresponding EOF1 and EOF2 patterns (EOFs are not shown for brevity). In the ‘strong’ case, the two maxima have almost equal probability. The maxima with normalized PC1 close to 1 and PC2 close to zero represent a strong ‘active’ condition (Figure 5 *a*). The other maxima represent a very weak ‘break’ pattern. Although the two patterns have equal probability, the strong ‘active’ pattern would have a dominating influence on the seasonal mean. For the ‘weak’ monsoon case, the maximum with both PC1 and PC2 close to zero represents a transition pattern. Both

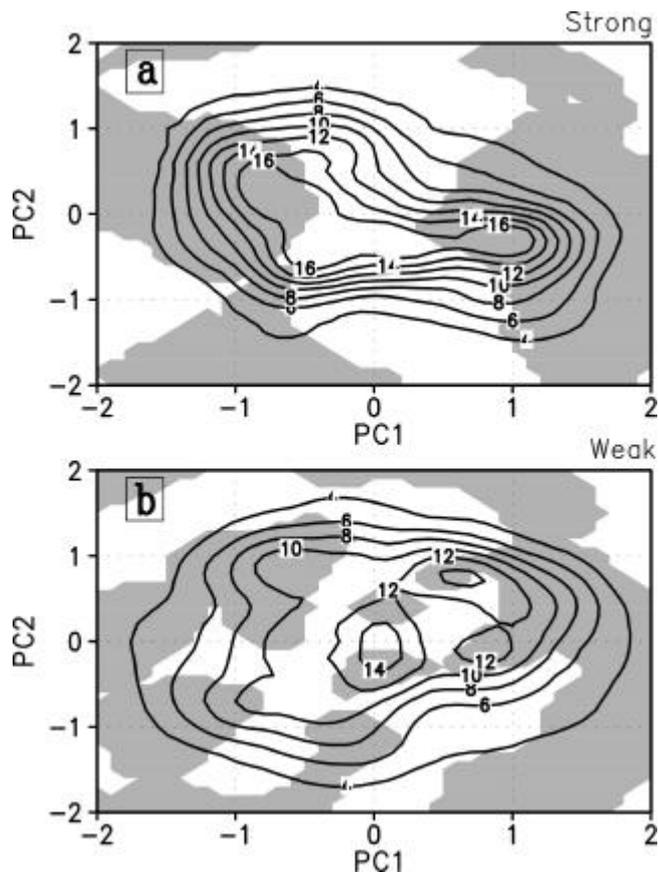


Figure 4. Two-dimensional PDFs of the atmospheric state vector spanned by the two dominant EOFs of low-level vorticity. *a*, 7 ‘strong’; *b*, 10 ‘weak’ monsoon years. The smoothing parameter used is $h = 0.6$ and the PDFs are multiplied by a factor of 100. Shading represents regions where the observed PDF is significant with 90% confidence.

the other maxima represent strong ‘break’ conditions. One such ‘break’ with both PC1 and PC2 making approximately equal contribution is shown in Figure 5 *b*. Thus, the ‘strong’ monsoon years are clearly associated with higher frequency of occurrence of ‘active’ conditions while ‘weak’ monsoon years are clearly associated with higher frequency of occurrence of ‘break’ conditions. The results obtained from low-level vorticity alone are supported when convection (OLR) is also included in defining the ISOs. However, OLR data are available only from 1974. Within this period (1974–1997), we have six ‘weak’ monsoon years ($IMR < -1.0$ SD). To enhance the sample of ‘strong’ years within this period, the criterion was relaxed to include years with $IMR > 0.5$ SD. With this definition, we have identified six strong years. Combined EOF of the ISO filtered vorticity and OLR was carried out and PDFs were calculated based on the first two PCs. These results (figure not shown) again show that the ‘strong’ (‘weak’) monsoon years are dominated by a higher frequency of occurrence of ‘active’ (‘break’) conditions.

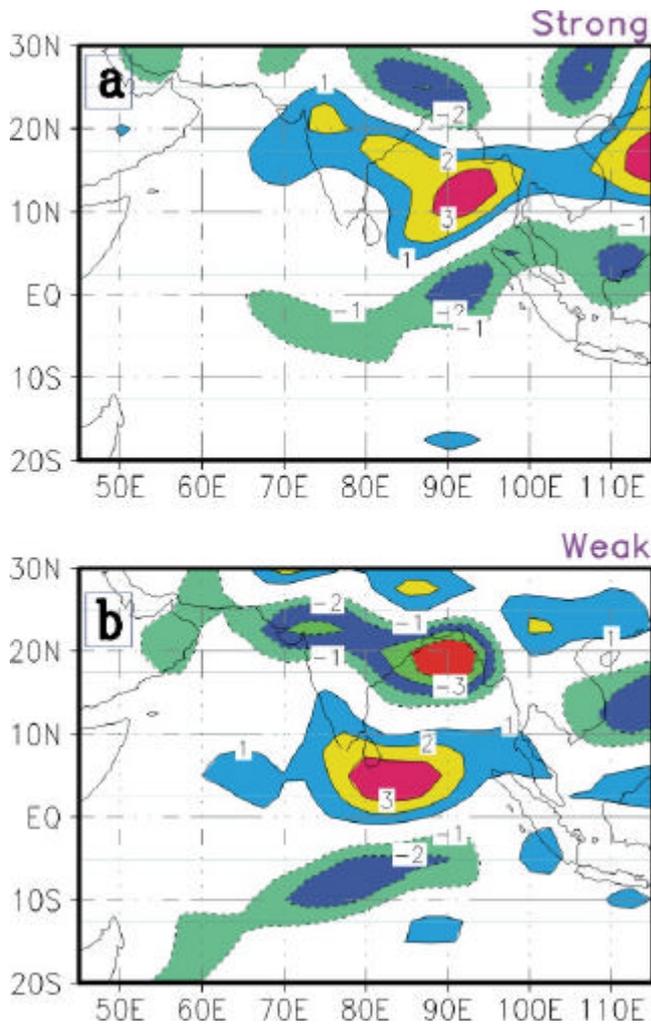


Figure 5. Geographical patterns of the dominant regimes for low-level relative vorticity ($1.0 \times 10^{-6} \text{ s}^{-1}$) shown in Figure 4; *a*, for 'strong' monsoon years; *b*, for 'weak' monsoon years.

The underlying spatial pattern of the dominant ISO mode invariant from event to event and from one year to another is highlighted. It is associated with a systematic northward propagation of the TCZ from the southern position to the northern position (monsoon trough). The 'active' ('break') phase of the oscillation is associated with enhanced cyclonic vorticity and convection in the northern position of the TCZ and enhanced anti-cyclonic vorticity and reduced (enhanced) convection over the southern position of the TCZ. It is further shown that the intra-seasonal and inter-annual variations of the monsoon are governed by a common mode of spatial variability. Finally, using long record of daily circulation data (1956–1997) and convection data (1979–1997) that includes a large number of 'strong' and 'weak' monsoon years, it is shown that 'strong' ('weak') monsoon years are characterized by higher

frequency of occurrence of 'active' ('break') conditions.

Thus, for the first time, we show convincing evidence from long record of daily observations that the frequency of intra-seasonal regimes determines whether it will be a 'strong' or 'weak' Indian summer monsoon. As the seasonal mean monsoon is governed partly by external forcing and partly by the ISOs, even if the strong (weak) monsoons are not clearly characterized by higher frequency of the 'active' ('break') conditions, the role of ISOs could not be ruled out. The fact that even after separating the contribution of the external forcing, strong (weak) monsoons are clearly characterized by higher frequency of 'active' ('break') conditions, indicates that the ISOs play a dominant role in determining the seasonal mean. As the ISOs are intrinsically chaotic, the prediction of inter-annual variations of the Indian summer monsoon will always be difficult and will have to be probabilistic in nature. The dominant role of the ISOs indicates that, to simulate the seasonal mean monsoon realistically, atmospheric GCMs must simulate the spatial pattern as well as the amplitude of the ISOs realistically.

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