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INTRA-SEASONAL OSCILLATIONS AND PREDICTABILITY OF THE INDIAN SUMMER MONSOON

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While the dynamical climate models are being increasingly successful in predicting the seasonal climate of many regions of the tropics, the dynamical prediction of the Indian summer monsoon remains a frustrating experience. Modelling and observational evidence is presented here to support a hypothesis that the vigorous monsoonal intra-seasonal oscillations (ISO's) sets a limit on predictability of the Indian summer monsoon by producing 'internal' low frequency variability that is often comparable or even larger than those produced by the predictable slowly varying boundary forcings. Two long simulations of an atmospheric general circulation model one of which had no inter-annual forcing (either external or emanating from the lower boundary), are used to estimate the ratio between 'internal' and 'external' variability. This ratio is found to be close to one over the Indian monsoon region indicating that the Indian summer monsoon may be only marginally predictable. Using a nonlinear dynamical system model it is shown that the large low frequency 'internal' variability may arise from an interaction between the ISO's and the annual cycle. Daily observations of circulation for 33 years and outgoing long-wave radiation (OLR) data for 24 years are then used and a method is presented to estimate this ratio from observations. It is shown that the monsoonal ISO's primarily contribute to the 'internal' low frequency variability and that the ratio between the 'internal' and 'external' variability is close to one over the Indian monsoon region. To derive further insight how the ISO's affect the seasonal mean monsoon, the structure of spatial and temporal variability of the ISO's are studied in relation to those of the seasonal mean monsoon. It is shown that the spatial structure of the dominant ISO mode and that of inter-annual variations of the seasonal mean monsoon are very similar. Thus, a higher probability of occurrence of 'active' ('break') condition in a season may lead to a stronger (weaker) seasonal mean monsoon. Probability density estimates show that strong (weak) monsoon years are indeed associated with higher probability of occurrence of 'active' ('break') conditions. The study leads to the disturbing conclusion that the Indian summer monsoon may continue to be a difficult system to predict.

Key Words: Indian Summer Monsoon; Predictability; Intra-Seasonal Oscillations

1 Introduction

Prediction of the seasonal mean monsoon precipitation with lead-time of even one or two season has tremendous socio-economic implications. For a long time such predictions have been made using statistical techniques, such as linear or nonlinear multiple regression techniques[1]. The relationship between the predictors used in these techniques and the Indian monsoon undergo slow changes on decadal time scales and so does the efficiency of the statistical models[2]. With the advances made in three dimensional climate modelling during the past three decades, the dynamical simulation and prediction of Indian summer monsoon is naturally being attempted. While, models have been successful in simulating the seasonal mean and its inter-annual variability in several tropical regions[3], most models find the simulation of mean monsoon precipitation extremely difficult and have even greater difficulty in simulating the inter-annual variability of Indian summer monsoon rainfall[3-5]. What limits the simulation and predictability of the Indian summer monsoon? In this article, we attempt to provide some answer to this question. First, a conceptual framework for dynamical predictability of monthly or seasonal climate is described.

The predictability of weather (or the instantaneous state of the atmosphere) is limited to about two weeks[6,7] due to inherent instability and nonlinearity of the system. The atmosphere possesses significant low frequency variability. If the low frequency variations of the monthly and seasonal means were entirely governed by scale interactions of the higher frequency chaotic weather fluctuations, the time

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averages will then be no more predictable than the weather disturbances themselves. However, it appears that a large fraction of the low frequency variability, especially in the tropics, may be forced by slowly varying boundary conditions such as the sea surface temperature (SST) and soil moisture variations. Hence, the predictability of climate (e.g. space-time averages) is determined partly by chaotic internal processes and partly by slowly varying boundary forcings such as the SST, sea ice and soil moisture. This understanding that anomalous boundary conditions (ABC) may provide potential predictability has formed the scientific basis for deterministic climate predictions[8-10]. Research during the past decade has shown that the climate in large part of tropics is primarily determined by slowly varying SST forcing[11] where potential for making dynamical forecast several seasons in advance exists. However, during the same period, we have also learnt that there are regions within the tropics, climate of which is not strongly governed by ABC. The Indian summer monsoon is such a system[12,13,5]. The intra-seasonal oscillations (ISO's) such as the east-ward propagating Madden-Julian Oscillations (MJO's) and the north-ward propagating monsoonal ISO's with period in the range of 30 to 60 days are quite vigorous in the tropics. Both the MJO's as well as the monsoonal ISO's are known to be driven by internal feedback between convection and dynamics[14,15]. Therefore, in addition to the scale interactions between weather disturbances, time averaging of the chaotic ISO's can contribute to the low frequency variability of monthly and seasonal means in the tropics.

The predictability of tropical climate, therefore, depends on the relative contributions of 'internal' dynamics and 'external' slowly varying forcing to the inter-annual variability. In the present study, we estimate the ratio between 'internal' and 'external' components of inter-annual variability using two independent methods. First, this ratio is estimated from two long integrations of a state of the art atmospheric general circulation model. These results are described in Section 2. Then, long (33 years) homogeneous daily observations are used to estimate this ratio from observations (Section 3). Both model and observations indicate that this ratio is close to one in the Indian monsoon region. The observations also indicate that the 'internal' component of inter-annual variability comes from the intra-seasonal oscillations. Finally, in Section 4, we show how the monsoonal ISO's actually lead to modification of the seasonal mean and thereby influence inter-annual variability of the Indian summer monsoon.

2 Estimate of Predictability Using an Atmospheric General Circulation Model

It is relatively easier to estimate the ratio between 'internal' and 'external' contributions to the inter-annual variability from a long integration of an atmospheric general circulation model (AGCM) with observed boundary condition and another long integration with fixed boundary condition[5] or from an ensemble of long integrations of the same AGCM with same observed boundary conditions but differing only in the initial conditions[16-18]. Kumar and Hoerling[19] estimated the ratio between the 'external' and 'internal' variability for the extra-tropics using a large ensemble of long simulations by an AGCM. In this section, we present results from two long integrations of the Geophysical Fluid Dynamics Laboratory (GFDL)'s AGCM.

The GFDL climate model used in this study is a spectral model where the dynamic computations are performed using so called spectral element method. This version has a rhomboidal 30 horizontal resolution (30 zonal waves and 30 associated Legendre functions, approximately 3.75° longitude by 2.25° latitude resolution) and 14 unevenly spaced sigma levels in the vertical. More details about the model and the physical parameterizations used are described in Goswami[5]. Additional details about the model can also be found in Gordon and Stern[20], where an earlier version of the model is described. Two experiments carried out with the model are briefly described below.

OBS-SST Run: In this run observed monthly mean sea surface temperature (SST) is prescribed. Soil moisture and snow cover are predicted. The model was integrated for 15 years (January 1979 to December 1993) with these boundary conditions. The low frequency inter-annual variations in observed SST associated with the El Nino and Southern Oscillation (ENSO) force low frequency inter-annual variations in the model atmosphere in this run.

CLI-SST Run: In this run mean seasonal cycle of giobal SST is prescribed and repeated every year. Soil moisture and snow cover are predicted. The model was initiated from a resting isothermal condition and was integrated for a period of 40 years. The results from the last 20 years are presented here after the model reached a quasi-equilibrium. As there is no external inter-annual forcing in this run, any simulated inter-annual variability must arise from internal dynamics. However, as soil moisture is interactive, some inter-annual variability may arise due to interaction between soil moisture and radiation.

In order to get a quantitative estimate of the ratio between 'internal' and 'external' contributions to the monsoon variability, several indices of the Indian summer monsoon simulated by the OBS-SST run and CLI-SST run were compared. This is summarized in Table I. It is seen that the standard deviation of inter-annual variability of monsoon indices simulated by the CLI-SST run (internal variability) varies from 0.7 to 0.8 of that simulated by the OBS-SST run (total inter-annual variability). This indicates that 50-60 percent of the observed inter-annual variability may be due to internal dynamics. This is further illustrated in Fig. 1, where the standard deviation of June-July-August (JJA) precipitation simulated by OBS-SST run is shown together with the ratio between standard deviation of JJA precipitation simulated by OBS-SST run and that by the CLI-SST run. The ratio is large and significant in the central and eastern equatorial Pacific, representing a region where the summer precipitation is predictable as the external variability is much larger than the internal variability in this region. Over the Indian monsoon region this ratio is close to 1.5 indicating that 50 per cent or more of the total inter-annual variability is determined by internal dynamics. Thus, the predictability in this region is marginal at best.

Table I

Inter-annual Standard Deviation of Some Monsoon Indices Averaged for JJAS (June-July-August-September)

Index & Averaging Area	OBS-SST	CLI-SST
Precipitation Anom over India (70-95°E, 10-30°N)	1.01 mm day^{-1}	0.82 mm day^{-1}
Low Level Jet Index, U_{860} Anom (60°E, 10-20°N)	0.87 ms^{-1}	0.61ms^{-1}
Broad Scale Monsoon Index (U_{170}-U_{860}) Anom (40-110°E, 0-20°N)	2.41 ms^{-1}	1.92 ms^{-1}
TEJ KE at 170 mb	Mean=348.3m^{2}s^{-2}	Mean=382.9m^{2}s^{-2}
$(U^2_{170}+V^2_{170})/2$	-	-
(30-150°E, 5°S-15°N)	SD=42.1 m^{2}s^{-2}	SD=29.6 m^{2}s^{-2}
Monsoon KE	Mean=561.7m^{2}s^{-2}	Mean=605.1m^{2}s^{-2}
$(U^2_{860}+V^2_{860}+U^2_{170}+V^2_{170})/2$	-	-
(5-15°N, 40-110°E)	SD=54.2 m^{2}s^{-2}	SD=41.5 m^{2}s^{-2}

In the absence of any external forcing how does the atmosphere generates inter-annual variability of significant amplitude? To gain insight regarding this question, the nature of the low frequency variability in the CLI-SST run is first examined. Time series of three different area averaged quantities from the CLI-SST run are shown in Fig. 2 after applying a 5-month running mean filter. A preliminary examination indicates the presence of a significant quasi-biennial oscillation in all three-time series. Spectra of the unfiltered time series (Fig. 3) confirm that the model atmosphere exhibits an internal quasi-biennial oscillation of significant amplitude. The model results were further analyzed to gain insight regarding the mechanism responsible for the internal quasi-biennial oscillation. These analysis indicate that a modulation of intra-seasonal activity by the seasonal cycle leads to the model low frequency quasi-biennial variability. This possibility of generating a quasi-biennial oscillation due to modulation of chaotic ISO's by an annual variation of the forcing was demonstrated with a simple nonlinear dynamical model (see ref. [21]).

The AGCM calculations indicate that 'internal' variability in the Indian monsoon region is comparable to the 'external' variability and limits the predictability of the Indian summer monsoon. How much can we trust these model estimates? Could model systematic errors have influenced these estimates? To gain confidence on these estimates, we make similar estimates from long daily observations. These results are presented in the next section.

3 Estimates of Predictability from Observations

Making unambiguous estimates of the 'internal' and 'external' components of variability from observations is rather difficult. Madden[22,23], Madden and Shea[24] and Shea and Madden[25] attempted to estimate the two variances in some extra-tropical regions. They estimated synoptic scale internal variability from short time series (such as within a season) and extrapolated the power spectrum to lower frequencies by assuming a white noise extension. This approach is simple but assumes that the low frequency power spectrum would be white and it could be extrapolated from power at higher frequencies. Shukla[26] commented at length on Madden's approach and argued that the methodology used and assumptions made by Madden could have overestimated the natural variability or 'climate noise'

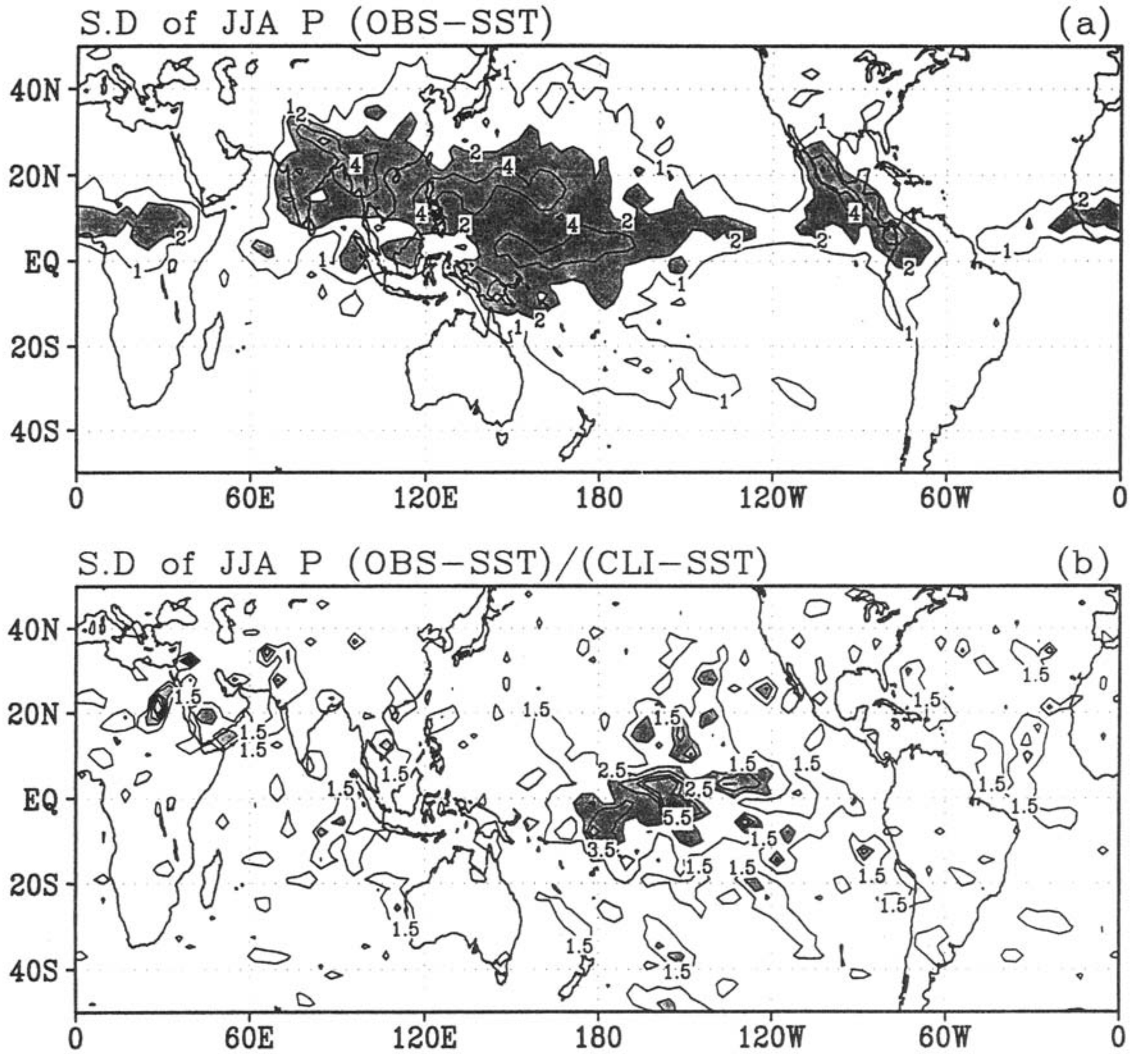

Fig. 1 (a) Standard deviation of June-July-August (JJA) precipitation (mm.day^{-1}) simulated by OBS-SST run. Contours greater than 2 mm.day^{-1} are shaded (b) Ratio between standard deviation of JJA precipitation simulated by OBS-SST and that of CLI-SST. Ratios greater than 2.5 are shaded.

and thereby underestimated the potential predictability. Madden[27] while disagreeing with Shukla that his method underestimated the potential predictability agreed that there is considerable uncertainty in separating the so called 'climate noise' from the climate signal. More general low frequency extension of the intra-seasonal variance to estimate the level of 'climate noise' was used by others[28,29]. Trenberth[30] points out that these estimates depend crucially on the use of correct value of T_0, the effective time between independent data. He pointed out that these studies might have underestimated T_0 by using negatively biased estimates of the lagged auto correlations by improperly removing the annual cycle and inter-annual variability.

The main data used in this study are the daily low level zonal winds (850 hPa) from NCEP/NCAR reanalysis[31] for 33 years (1965-1997). Here, we propose a method to separate the 'externally forced' monthly mean anomalies from raw daily data. Our methodology is based on the following premise. The anomalies associated with the synoptic and intra-seasonal oscillations may be defined as the deviations from the annual cycle. In the present study, the annual cycle is defined as the sum of the first three harmonics of daily data for each year. We hypothesize that the inter-annual variations of the seasonal cycle are essentially due to the slowly varying boundary forcing. The dominant slowly varying boundary forcing in the tropics is that associated with the El Nino and Southern

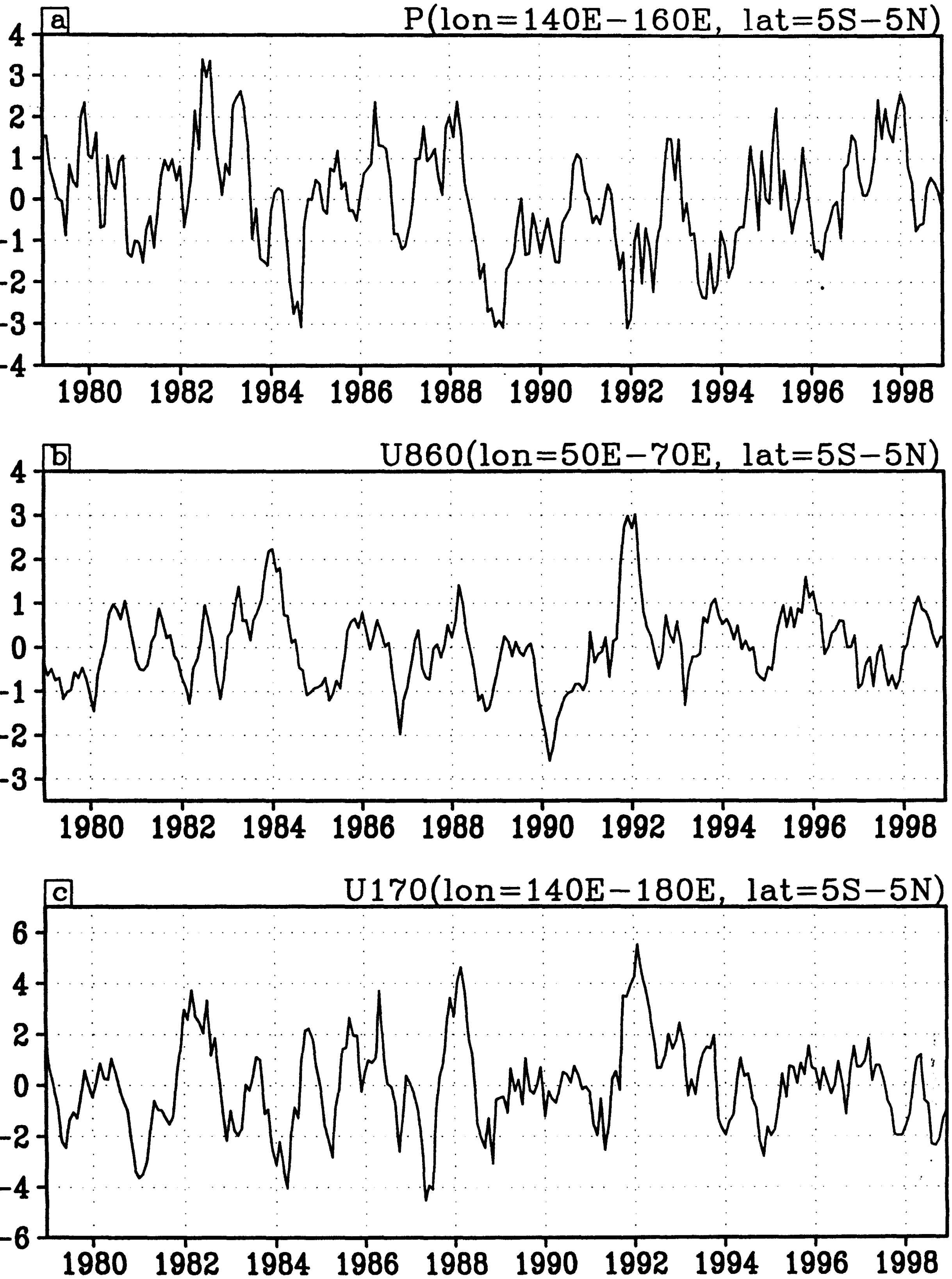

Fig. 2 Five month running mean of filtered anomalies averaged over three regions from the CLI-SST simulation. (a) Precipitation ($mm.day^{-1}$), (b) Zonal wind in the lower atmosphere (at 860hPa model level, ms^{-1}) and (c) Zonal wind in the upper atmosphere (at 170hPa model level, ms^{-1}).

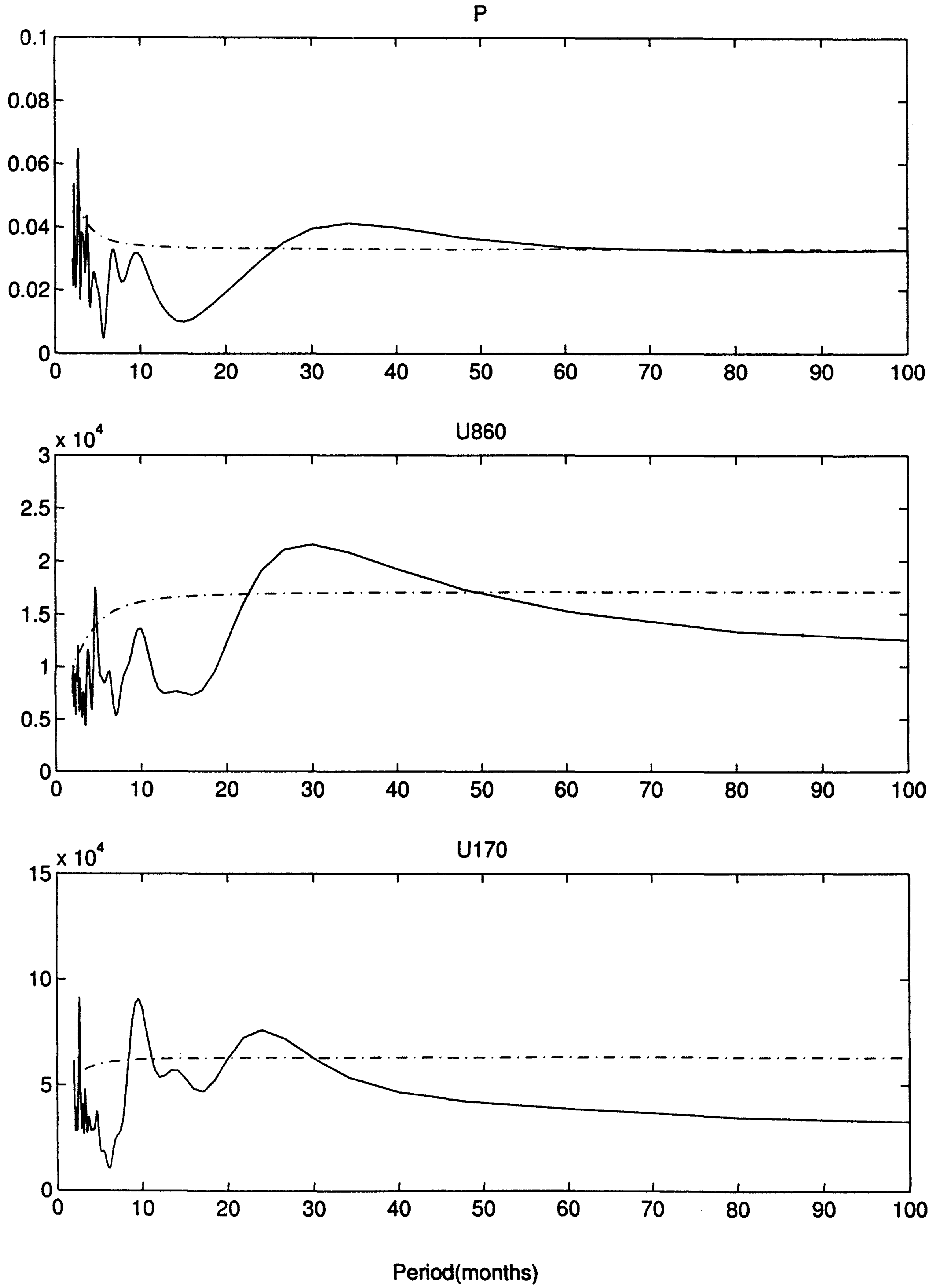

Fig. 3 Power spectral density of the unfiltered area averaged anomalies shown in Fig.1. The dashed curve in each case shows 95% confidence level using red noise spectrum as null hypothesis.

Oscillation (ENSO) related SST variations. Since the time scale of variations of the boundary forcing is much longer (3-4 years to decadal) than that of the annual cycle, it essentially results in modulation of the annual cycle. Thus, the inter-annual variations introduced by the 'external' (slowly varying) forcing can be estimated from the monthly means constructed from the deviations of the individual annual cycles from the climatological mean annual cycle. The annual cycle of zonal winds at 850 hPa each year from 1965 to 1997 are calculated. From the daily annual cycles of all the years, a climatological mean daily annual cycle is constructed. Monthly 'external' anomalies are estimated as individual monthly means of deviations of the individual annual cycles from the climatological annual cycle. Monthly 'internal' anomalies are defined as the monthly mean of daily anomalies defined as deviations of daily observations from annual cycle of individual years. An underlying assumption in this procedure of linear reparability is that the statistics of the ISO's are neither significantly affected by the slowly varying 'external' forcing nor do they affect the 'external' response significantly.

The total inter-annual variance may be estimated in two ways. The traditional way of calculating it is to construct monthly mean data from the raw daily observations. Then construct a climatological monthly mean annual cycle. Deviations of the monthly means from this climatological monthly mean annual cycle are the total monthly mean anomalies. The total inter-annual variance may be calculated from these total anomalies. Alternatively, daily anomalies can be constructed with respect to the daily climatological mean annual cycle. The monthly mean anomalies obtained from these daily anomalies give us the total monthly anomalies.

The total variance of monthly means as well as the 'internal' and 'external' components of the variance of zonal winds at 850 hPa are calculated as described in the previous section based on daily data for 33 years (1965-1997). It is seen (figure not shown) that the sum of the 'external' and 'internal' variances almost exactly equals the total variances in all geographical locations in the tropics. Let us define a 'predictability index'

$$\Gamma = \sigma_e^2 / \sigma_i^2 .$$

Larger the value of this ratio compared to unity, higher the predictability. The monthly mean climate may be considered marginally predictable if gamma is of the order one. If gamma is less than one, the climate would be unpredictable as the 'internal' variability exercises a dominating influence on the total monthly variability in this case. We calculated the ratio between the 'external' and the 'internal' variances taking all months together (Fig. 4a) and then taking all the northern hemispheric (NH) winter months (December-January-February) together (Fig. 4b) and all summer months (June-July-August) together (Fig. 4c). As expected, Fig. 4a shows that the predictability is high in the regions where the ENSO influence is large. These include equatorial Pacific between 10°N and 10°S, equatorial Atlantic and equatorial Indian Ocean east of 70°E. Parts of Africa also indicate high predictability as this region is also known to have strong ENSO influence. Probably the most important information provided by this figure is identification of the regions over which the monthly climate is likely to be unpredictable. These are essentially the monsoon regions of the world, namely, the Indian summer monsoon region, the east Asian monsoon region, the central American monsoon region and the Australian monsoon region. In these regions, the ratio is between 1 and 1.5 .The smallest ratio is found over the Indian monsoon region where it goes down to even less than 1. The pattern of this ratio during NH summer and winter are significantly different as shown in Fig.4b and 4c. It may be noted that during the NH summer, not only the peak values of the predictability index, 'Γ' is higher than the peak value during northern winter, the area covered by 'Γ' greater than two is much larger during NH summer compared to that in NH winter. Thus, during NH winter the monthly mean predictability not only decreases compared to that in NH summer, the predictable region also shrinks. Poor predictability over the Indian monsoon region, however, appears to be robust feature and remains unchanged during both seasons.

The qualitative difference in the predictability regimes during NH summer compared to NH winter is probably not very surprising if we take into account the seasonality of the 'external' and the 'internal' variances. We do not expect much seasonality in the 'external' variance as it arises from a slowly varying signal (with time scales longer than a year). However, the 'internal' variance has a pronounced seasonality (Fig. 5). Barring Indian monsoon region and a small region in the American monsoon region, the internal variability is very weak throughout the equatorial wave-guide during NH summer. This explains the larger magnitude and extension of 'Γ' during NH

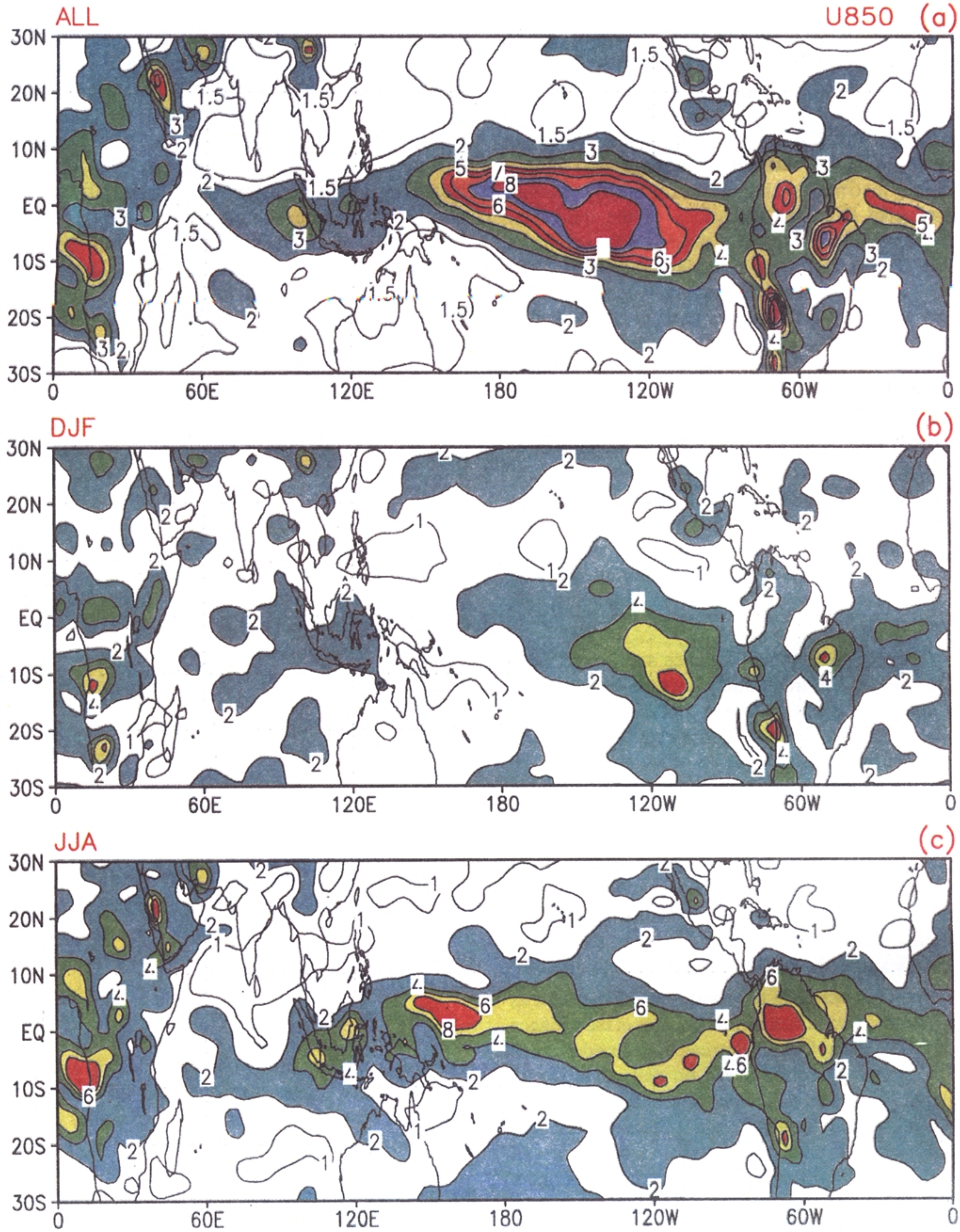

Fig. 4 The 'predictability index' (σ^2_e / σ^2_i) for zonal winds. (a) based on all months. (b) for all Northern Hemisphere winter months (December-January-February). (c) for all Northern Hemisphere summer months (June-July-August).

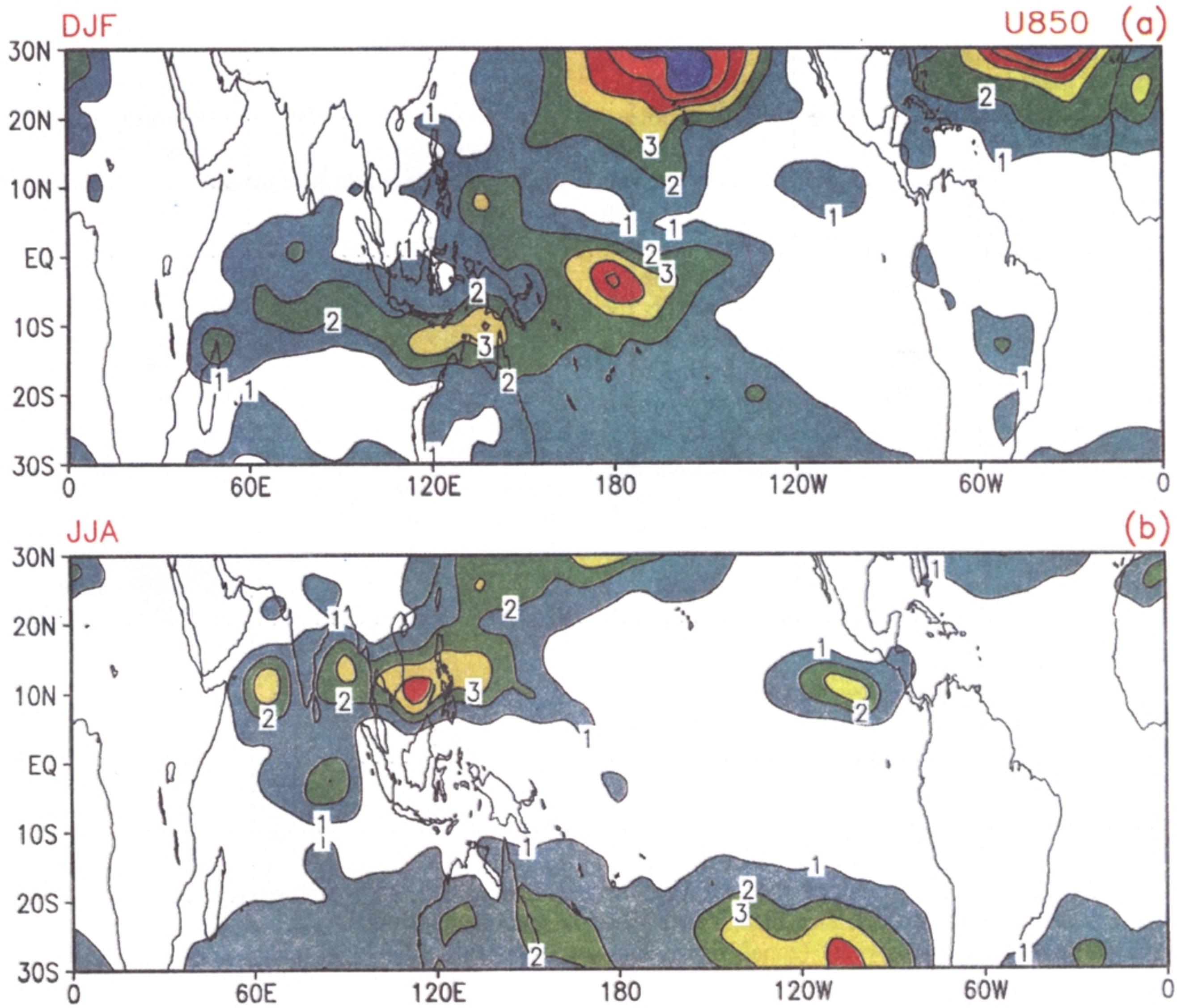

Fig. 5 The 'internal' variance of zonal winds at 850 hPa (m^2s^2) during (a) NH winter months (December-January-February) and (b) during NH summer months (June-July-August).

summer (Fig. 4c). On the other hand, the 'internal' variance during NH winter are quite strong from Indian Ocean to central Pacific, primarily over the Australian monsoon region and the south Pacific convergence zone (SPCZ). The larger 'internal' variability during NH winter is consistent with the fact the ISO activity in tropics is strong during boreal winter and spring and weak during boreal summer except over the Indian monsoon region[32,33]. Even though the 'external' variance remains similar in magnitude and extent in winter compared to those in summer, the 'predictability index' becomes smaller and the predictable region shrinks to a smaller region in the far eastern Pacific due to vigorous 'internal' activity in Indian Ocean and central and western Pacific.

4 How do the Monsoonal ISO's Modulate Seasonal Mean Monsoon

The AGCM simulations as well as the observations indicate that the monsoonal ISO's are responsible for the high level of 'internal' low frequency variability in the Indian monsoon region. How do the ISO's affect modulation of the seasonal mean? In this section, we present a conceptual model showing how the ISO's modulate the seasonal mean and provide supporting evidence for the same from observations.

June to September (JJAS) mean monsoon precipitation has a major zone of maximum precipitation (see Fig. 1a in ref. [34]) from north Bay-of-Bengal extending westward along the Gangetic valley (called 'monsoon trough', a region of quasi-stationary cyclonic vorticity) and a secondary maximum south of the equator (between 0° and 10°S) over the warm waters of the Indian Ocean (also a region of quasi-stationary cyclonic vorticity in the southern hemisphere). The two maxima in seasonal mean precipitation represent two favoured locations of the tropical convergence zone (TCZ)[35]. The ISO's are manifestations of fluctuations of the TCZ within the season between the two favoured locations that act as two attractors for the ISO's. The fluctuations of the ISO's between the two favoured locations are also accompanied by a movement from the southern to the northern position. The statistics of the ISO could influence the seasonal mean if the spatial structure of the ISO is such that in one phase (the 'active') it strengthens the northern TCZ and weakens the southern one while in the another phase (the 'break') it weakens the northern TCZ and strengthens the southern one. On a given Indian summer monsoon season (defined here as the period between June 1 and September 30), a larger probability of occurrence of 'active' ('break')-like conditions over that corresponding to 'break' ('active')-like ones may lead to a stronger (weaker) than normal seasonal mean.

This possibility is tested with daily observations of circulation and convection for 24 years (1974-1997). Two dominant ISO modes, one with period between 30 and 60 days and another with period between 10 and 20 days are identified from daily NCEP/NCAR reanalyzed winds (zonal, meridional and vertical components) at lower (850 hPa), middle (500 hPa) and upper (200 hPa) atmosphere and from daily observed outgoing long-wave radiation (OLR) from satellite[36] for the same period. The mean spatial patterns of circulation and convection associated with the 'active' and 'break' monsoon conditions are brought out using a phase composite technique[37]. An 'active' (a 'break') monsoon condition is expected to be associated with stronger (weaker) westerlies south of the monsoon trough as it strengthens (weakens) the trough. We define 'active' ('break') days as those days when the 30-60 day filtered zonal winds at a reference point south of the monsoon trough (e.g. 90°E, 15°N) is greater than +1 (less than -1) standard deviation. Large scale pattern of the mean circulation anomalies associated with the 'active' and 'break' conditions in a particular year are then obtained by constructing composite of anomalies at all points for all 'active' and all 'break' days. Long term mean of all such composites for 20 years is then constructed. Such climatological mean composites for an 'active' (a 'break') condition (Fig. 6a) is associated with a general strengthening (weakening) of the large scale mean monsoon circulation. A noteworthy feature is that the circulation changes are not confined only over the Indian region but extends even to east of 120°E. Climatological mean composite OLR anomalies corresponding to 'active' and 'break' conditions as defined by our circulation criterion shows (Fig. 6b) that the circulation changes associated with the dominant ISO are also associated with coherent changes of convection. The enhanced low-level cyclonic (anticyclonic) vorticity in the northern TCZ during an 'active' (a 'break') condition gives rise to enhanced (decreased) ascending motion and enhanced (decreased) convection over the northern TCZ and decreased (enhanced) ascending motion leading to decreased (enhanced) convection over the southern TCZ. The 'active' and 'break' composites show that the spatial structure of the ISO anomalies are similar to that of the seasonal mean. This indicates that ISO's and inter-annual variations of the seasonal mean may be governed by a common mode of spatial variability. To test this possibility, the dominant empirical orthogonal function (EOF) of ISO variability and dominant EOF of inter-annual variability of seasonal mean vorticity at 850hPa were calculated and shown in Fig. 7. To get a better estimate of inter-annual variations of the seasonal mean, additional monthly data are added to cover a period of 40 years (1958-1997). This figure clearly shows that the ISO's and the inter-annual variations are governed by a common mode of spatial variability. As the spatial pattern of intra-seasonal and inter-annual variability are similar, frequency of occurrence of 'active' ('break') conditions can influence the seasonal mean. Other conditions (e.g. 'external' forcing) remaining normal, a higher probability of occurrence of 'active' ('break') conditions in a season would tend to lead to a stronger (weaker) than normal monsoon. Contribution from boundary forcing could either help or oppose the tendency of the ISO's to change the seasonal mean. Therefore, a lack of correlation between frequency of occurrence of 'active'/'break' conditions and strength of the seasonal mean would not indicate that ISO's have no influence on the seasonal mean. On the contrary, if 'strong' ('weak') monsoons are associated with higher probability of occurrence of 'active' ('break') conditions, it would be a sufficient reason to conclude that the ISO's have a dominating influence on the seasonal mean.

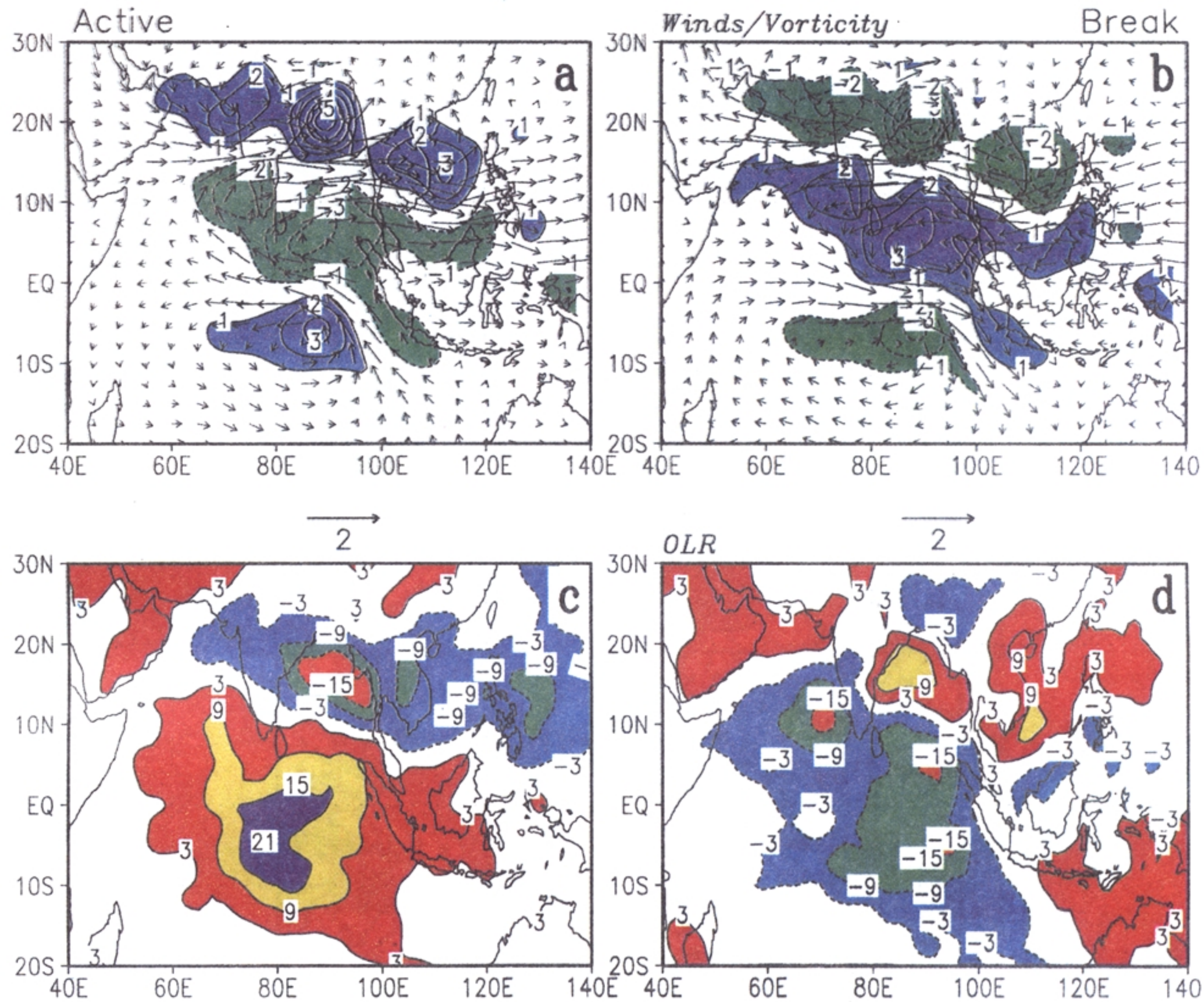

Fig. 6 (Upper panels) Climatological mean vector wind anomalies (arrows, ms^{-1}) at 850 hPa and associated relative vorticity (contours, $10^{-6}s^{-1}$) corresponding to 'active' and 'break' conditions for the 30-60 day mode taking into account all 'active' and 'break' conditions during the 20-year period (1978-1997). (Lower panels) Climatological mean OLR anomalies (Wm^{-2}) corresponding to 'active' and 'break' conditions taking into account all 'active' and 'break' conditions during the 19-year period (1979-1997).

To test this conjecture, probability density functions (PDF) of low-level (850 hPa) relative vorticity and OLR anomalies are examined for some 'strong', 'weak' and a combination of 'strong', 'weak' and 'normal' monsoon years. 'Strong' and 'weak', monsoon years are defined depending on whether the seasonal mean (June-September) all India rainfall (IMR) is more than 0.5 standard deviation (s.d) or less than -0.5 s.d. 'All' monsoon years is defined as a combination of 'strong', 'weak' and 'normal' years. In this manner, six weak years (1974, 1979, 1982, 1985, 1986, 1987) and six 'strong' monsoon years (1975, 1978, 1983, 1988, 1990, 1994) are selected during this period. Daily low-level vorticity and OLR filtered to keep periods between 10 and 90 days between 1 June and 30 September are then combined for the six years. A combined empirical orthogonal function (EOF) analysis using singular value decomposition technique[38] is carried out to define a reduced phase space based on the first two EOFs (explaining about 20% of total variance). The PDFs of the projection coefficients in the reduced phase space obtained using a Gaussian kernel estimator[39] and a smoothing parameter large enough to detect mutimodality with statistical significance are shown in Fig. 8(a). The PDFs of projection coefficients in the reduced space of similar data for the six 'weak' monsoon years are shown in Fig. 8(b) while those for 20 years with 6 'strong', 6 'weak' and 8 'normal' monsoon years is shown in Fig. 8(c). The PDFs for 'strong' and 'weak' monsoon

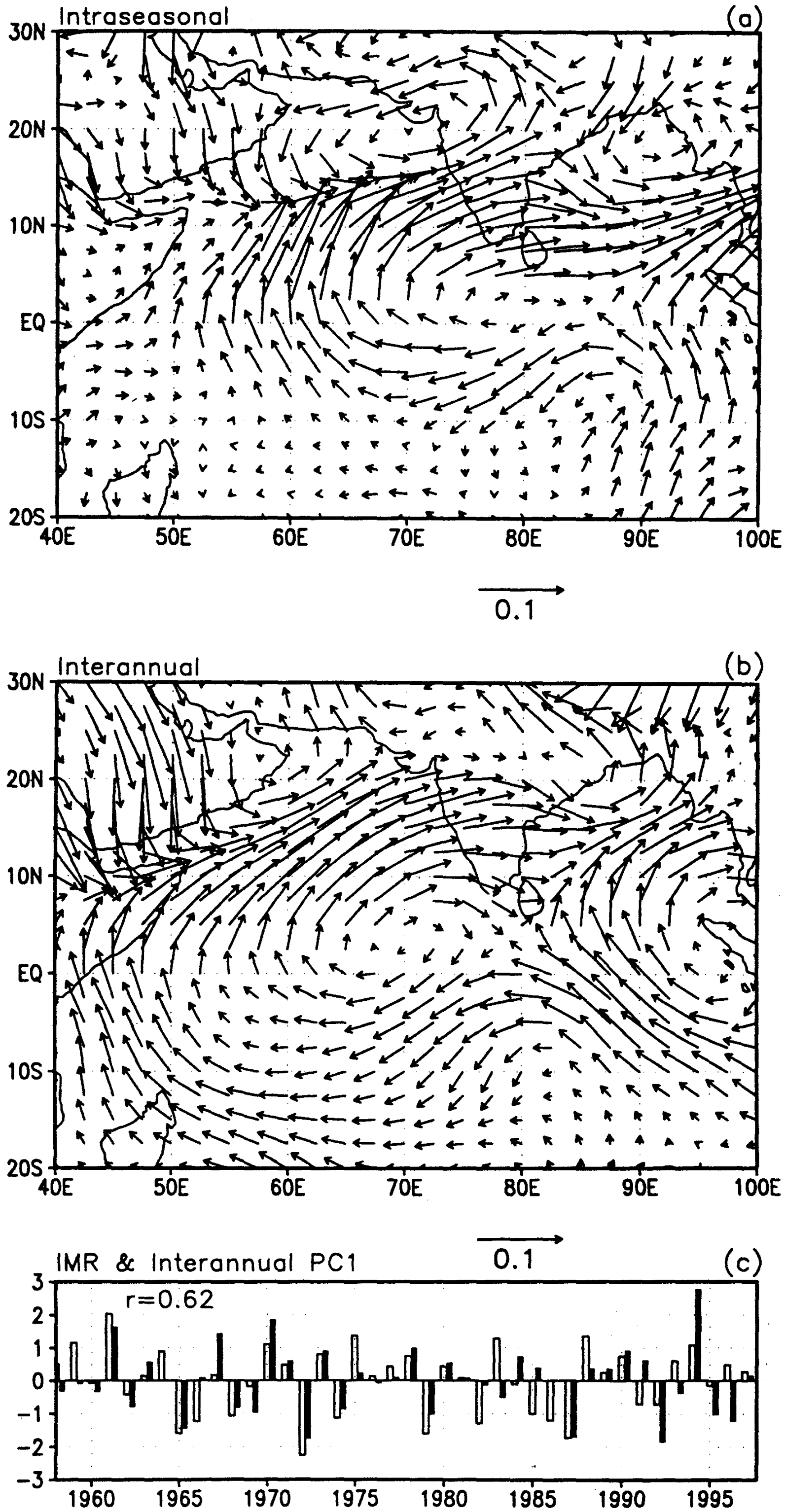

Fig. 7 First EOF of the intra-seasonal and inter-annual 850hPa winds. (a) Intra-seasonal EOFs are calculated with ISO filtered winds for the summer months (1 June to 30 September) for a period of 20 years (1978-1997). (b) Inter-annual EOFs are calculated with the seasonal mean (JJAS) winds for 40-year period (1958-1997). Units of vector loading are arbitrary. (c) Relation between All India Monsoon (JJAS) Rainfall (IMR)[40] and inter-annual PC1. Filled bars indicate inter-annual PC1 and the unfilled bar represent IMR. Both time series are normalized by their own standard deviation. Correlation between the two time series is shown.

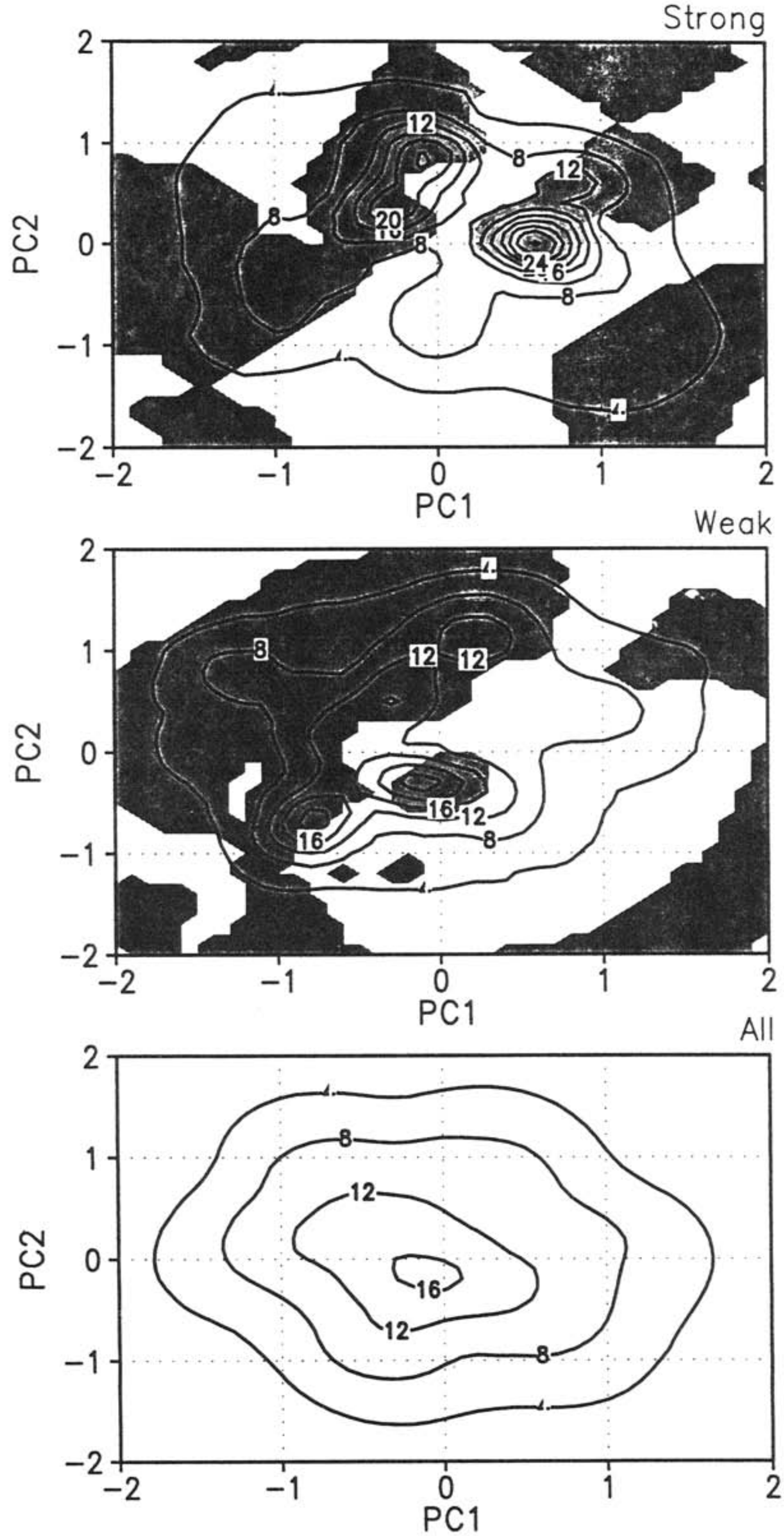

Fig. 8 Evidence of change in regimes of ISO's during 'strong' and 'weak' monsoon years. Illustrated are two-dimensional PDFs of the ISO state vector spanned by two dominant combined EOFs of low-level vorticity and OLR. PDFs are calculated with principal components normalized by their own standard deviation and taking the summer days (1 June to 30 September) for (a) 6 'strong' monsoon years (b) 6 'weak' monsoon years (c) 20 combined 'strong', 'weak' and 'normal' years (1978-1997). The smoothing parameter used is h=0.6 and PDFs are multiplied by a factor 100. The first two EOFs (not shown) are different in 'strong', 'weak' and 'all' years but are related to 'active' and 'break' conditions. The origin of the plots corresponds to a very weak state representing a transition between the two states (as in the 'all' case).

years are clearly multimodal with two major regimes in each case while those for 'all' years together is basically unimodal. It is interesting to note that the most probable pattern during 'strong' monsoon years correspond to an 'active ' pattern (Fig. 9a) while both the frequent patterns during 'weak' years correspond to 'break' patterns, the dominant amongst which is shown in Fig. 9(b). On the other hand, if all the years are taken together, we get only one most frequent regime that represents a transition from 'active' to 'break' or *vice versa.*

5 Conclusions

The seasonal mean summer monsoon precipitation over the Indian continent and the neighbouring regions is the lifeline of agrarian economy of the region. Prediction of seasonal mean monsoon precipitation, therefore assumes great importance. However, dynamical simulation and prediction of the seasonal mean monsoon has remained a challenging task for the atmospheric modellers. This article follows a three-pronged approach to make quantitative estimate on the limit on predictability of the Indian summer monsoon and shows that the monsoonal ISO's are responsible for limiting the predictability of the mean monsoon. Further, a physical picture is provided that shows how the ISO's modulate the seasonal mean monsoon.

The predictability of the Indian summer monsoon is governed by relative contribution of chaotic internal dynamics and slowly varying forcing to the inter-annual variation of the seasonal mean. Using two long simulations with an AGCM it is shown that the ratio between contribution of 'internal dynamics' and slowly varying 'external forcing' to low frequency inter-annual variations is close to 1 in the Indian monsoon region. Thus, 'internal dynamics' tends to make almost equal contribution to inter-annual variations of the seasonal mean as the 'external forcing'. This conclusion derived from an AGCM simulation is supported by a similar estimate of measure of predictability from long (33 years) daily observations. A method is presented to separate the 'internal' and 'external' contributions to inter-annual variability in the tropics and it is shown that the contribution of 'internal' low frequency variation is again closely comparable to that of 'external' forcing in the Indian monsoon region. It is further shown that the low frequency 'internal' variation in the Indian monsoon region essentially arise from

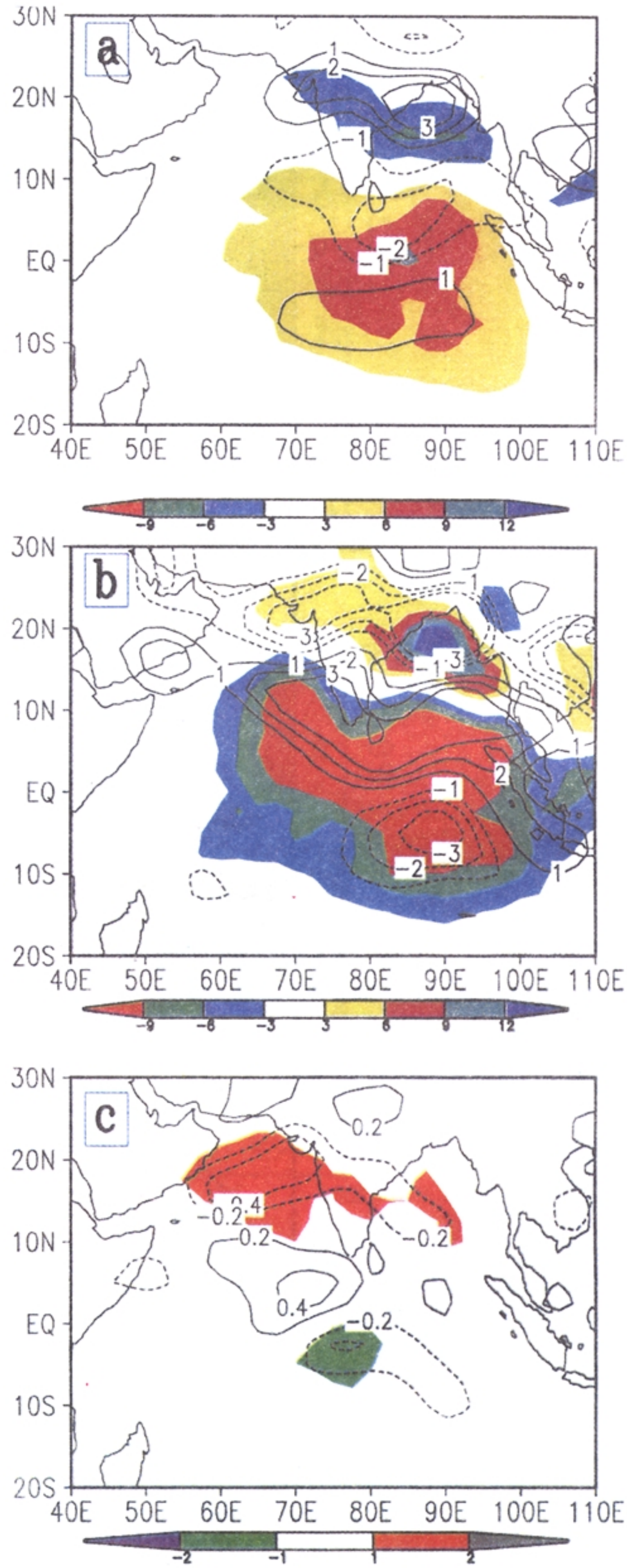

Fig. 9 Geographical patterns of the dominant regimes shown in Fig.8. (a) 'strong' monsoon years (b) 'weak' monsoon years (c) 'all' years. OLR patterns are shown as shaded contours (Wm^{-2}) while the corresponding low-level vorticity are shown in contours ($10^{-6}s^{-1}$).

time mean residuals of the ISO's. It is also shown that the ISO's could modulate the seasonal mean monsoon and hence it's inter-annual variability as both the intra-seasonal and inter-annual variations are governed by a common mode of spatial variability. As a result, if the frequency of occurrence of 'active' ('break') phases of ISO is larger than that of the opposite phases in a season, the seasonal mean monsoon could be 'strong' ('weak'). Probability density estimation shows that the 'strong' ('weak') monsoon years are indeed characterized by higher frequency of occurrence of 'active' ('break') conditions.

We provide first clear observational evidence that the monsoonal ISO's not only influence but dominate the inter-annual variability of the seasonal mean monsoon circulation and precipitation. Therefore, ability of GCM's to simulate the seasonal mean monsoon realistically would depend on their ability to simulate the statistics of the monsoonal ISO's realistically. In particular, they should be able to simulate the seesaw between the northern and southern positions of the TCZ correctly. Even if a GCM is successful in simulating the seasonal mean monsoon climatology, the simulation and prediction of inter-annual variability of the seasonal mean will continue to be difficult due to the chaotic contribution of the ISO's.

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