Chapter 1

MULTI-SCALE INTERACTIONS AND PREDICTABILITY OF THE INDIAN SUMMER MONSOON

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Abstract Following the seminal work of Charney and Shukla (1981), the tropical climate is recognised to be more predictable than extra tropical climate as it is largely forced by 'external' slowly varying forcing and less sensitive to initial conditions. However, the Indian summer monsoon is an exception within the tropics where 'internal' low frequency (LF) oscillations seem to make significant contribution to its interannual variability (IAV) and makes it sensitive to initial conditions. Quantitative estimate of contribution of 'internal' dynamics to IAV of Indian monsoon is made using long experiments with an atmospheric general circulation model (AGCM) and through analysis of long daily observations. Both AGCM experiments and observations indicate that more than 50% of IAV of the monsoon is contributed by 'internal' dynamics making the predictable signal (external component) burried in unpredictable noise (internal component) of comparable amplitude. Better understanding of the nature of the 'internal' LF variability is crucial for any improvement in predicition of seasonal mean monsoon.

Nature of 'internal' LF variability of the monsoon and mechanism responsible for it are investigated and shown that vigorous monsoon intraseasonal oscillations (ISO's) with time scale between 10-70 days are primarily responsible for generating the 'internal' IAV. The monsoon ISO's do this through scale interactions with synoptic disturbances (1-7 day time scale) on one hand and the annual cycle on the other. The spatial structure of the monsoon ISO's is similar to that of the seasonal mean. It is shown that frequency of occurance of strong (weak) phases of the ISO is different in different seasons giving rise to stronger (weaker) than normal monsoon. Change in the large scale circulation during strong (weak) phases of the ISO make it favourable (inhibiting) for cyclogenesis and gives rise to space time clustering of synoptic activity. This process leads to enhanced (reduced) rainfall in seasons of higher frequency of occurence strong (weak) phases of monsoon ISO.

Keywords:

1. Introduction

The Indian summer monsoon rainfall shapes the life, economy and culture of a large fraction of world's population. The wet summer and dry winter represent a large annual cycle characteristic of the Indian monsoon precipitation. The large annual cycle can be seen in other circulation parameters as well. The standard deviation (s.d.) of inter-annual variations of seasonal mean rainfall during June-September over Indian continent is not very large , approximately 10% of the long term mean ($\bar{P}$= 86 cm). The rainfall anomalies (departure from long term mean) during drought years (p' ¡ - 1.0 s.d) or flood years (p' ¿ + 1.0 s.d.) tend to have large spatial scale covering most of the continent (Shukla, 1987). The monsoon rainfall variations, therefore, have a strong influence on the agricultural productivity of the country (Gadgil, 2003; Webster et al., 1998). With the general decrease in the growth rate of agricultural productivity associated with the fatigue of the green revolution during the past decade, the rainfall variations may have even a larger impact on agricultural productivity in the coming years. As a result, prediction of summer monsoon rainfall at least one season in advance assumes great importance. For over a century, attempts have been made to predict monsoon rainfall using statistical methods involving local and global antecedent parameters that correlate with the monsoon rainfall (Blandford, 1884; Walker, 1923, 1924; Gowarikar et al., 1989; Sahai et al., 2003). The linear or nonlinear regression models as well as neural network based models (Goswami and Srividya, 1996) perform reasonably well when the monsoon is close to normal (about 70% of the past 130 year period) but fails to predict the extremes with useful skill. Thus, the usefulness of the statistical models is limited.

Dynamical prediction of seasonal mean monsoon using state-of-the art climate models offers the logical alternative to statistical forecasting of the monsoon. Unfortunately, the alternative approach has not shown better skill than the statistical models so far. Over the years the climate models have generally improved in simulating the mean climate and a series of sensitivity studies (Charney and Shukla, 1981; Shukla, 1981; Lau, 1985; Shukla, 1998) have shown that the tropical climate is , in general, much less sensitive to initial conditions and hence more predictable than the extra-tropical climate. This progress notwithstanding, almost all present day climate models have serious difficulty in simulating the seasonal mean monsoon climate and its interannual variations (Sperber and Palmer, 1996;Saji and Goswami, 1997; Gadgil and Sajani, 1998). Even though climate of certain tropical region show very little sensitivity to initial conditions (e.g. Shukla, 1998), the Indian summer monsoon appears to be quite sensitive to initial conditions (Sperber and Palmer, 1996; Sperber et al., 2001; Krishnamurthy and Shukla, 2001), making it the most difficult climate system to simulate and predict.

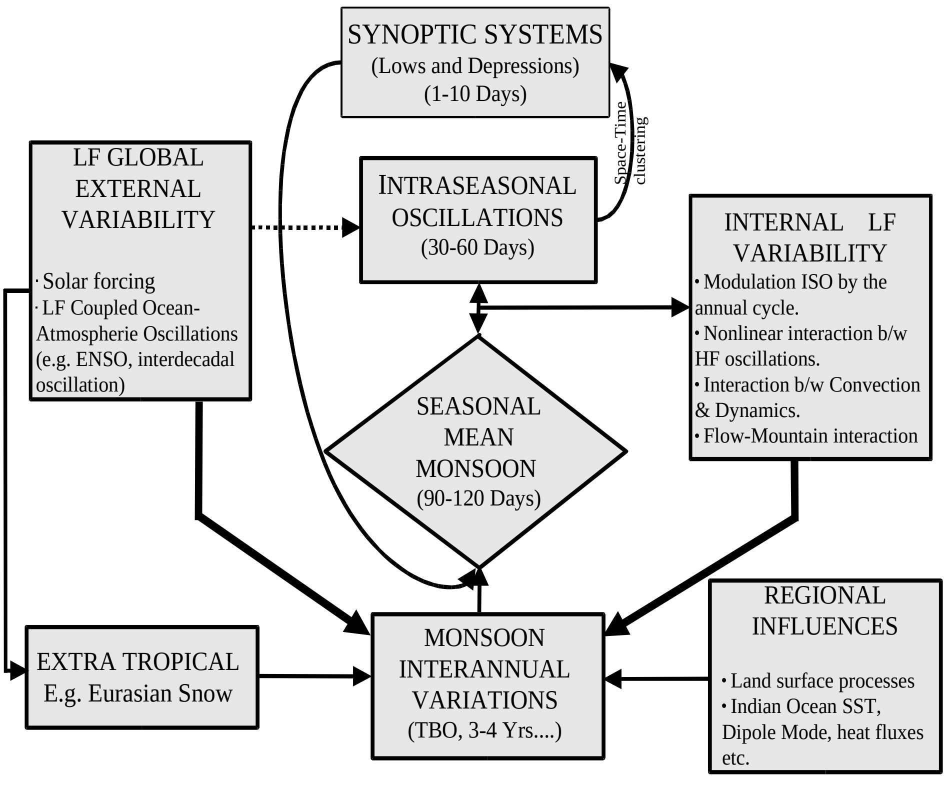

Figure 1.1. A schematic diagram indicating how monsoon ISO's influence the seasonal mean monsoon and its interannual variability by producing LF 'internal' variability through multi-scale interactions. Other 'external' forcing influencing the interannual variability of the monsoon are also indiacted.

The factors that determine the interannual variability and hence the predictability of the seasonal mean Indian monsoon are schematically illustrated in Fig.1. Two major components are LF 'external' variability and LF 'internal' variability that influence interannual variability of the monsoon. The contributions from 'external' variability such as solar forcing or slow coupled ocean-atmosphere oscillations (e.g. El Nino and Southern Oscillation (ENSO)) are less sensitive to initial conditions and hence more predictable. The contributions from LF 'internal' variability are sensitive to initial conditions and hence are unpredictable. Extra-tropical influence such as those associated with Eurasian snow cover (Hahn and Shukla, 1976; Kripalani et al., 1996) can also be considered 'external' as the snow variability in the extra-tropics may be governed by the sea surface temperature (SST) variability in the tropics (Meehl and Arblaster, 2002). In addition to these processes, there are some regional influences to interannual variability of the monsoon such as soil moisture-radiation feedback (Meehl, 1994) and Indian Ocean SST variability like the dipole mode (Saji et al., 1999). These could also be considered as 'external' forcing for monsoon variations. LF 'internal' variability of the monsoon can arise from a number of processes such as , nonlinear interaction between high frequency (HF) oscillations, interaction between organized convection and dynamics and interaction between flow and orography. In addition, northward propagating intraseasonal oscillations (ISO's) of monsoon (Yasunari,1979; Sikka and Gadgil, 1980; Goswami and Ajayamohan, 2001b) play an important role in generating LF 'internal' oscillations. Higher frequency of occurrence active (break) condition in a season can influence the seasonal mean monsoon rainfall as the monsoon ISO's cause space time clustering of rain producing synoptic disturbances. Further, modulation of the monsoon ISO by the annual cycle could also give rise to biennial type internal variability. The monsoon ISO's arise from internal processes in the atmosphere (Goswami and Shukla, 1984; Webster, 1983; Nanjundiah et al., 1992) through interaction between organized convection and dynamics. Thus, the LF variability generated by the ISO's is also of 'internal' origin with low predictability.

What makes the Indian monsoon such a difficult system to simulate and predict? The sensitivity of monsoon climate to initial conditions indicate existence significant 'internal' low frequency (LF) variability in the monsoon region. What is responsible for such 'internal' LF variability in the monsoon region? The predictability of the monsoon is going to be determined by the extent to which 'internal' LF variability govern interannual variability of the monsoon. To what extent is the monsoon predictable? Objective of the present article is to provide some answer to these questions. Quantitative estimate of contribution of 'internal' LF variability to interannual variability of monsoon will be made and mechanisms responsible for the 'internal' LF variability will be unraveled. Evidence will be presented to support a hypothesis that multi-scale interactions between synoptic variability (lows, depressions, time scale 1-10 days), intraseaonal oscillations (quasi-biwekly mode, 30-60 day mode) and the annual cycle largely results in the observed LF 'internal' variability.

If one could separate the 'internal' contribution to interannual variance, an estimate of predictability could be constructed as a ratio between the total interannual variance (the signal) and 'internal' variance (the noise). In this paper, we present such an estimate of predictability of the monsoon using a general circulation model (GCM) (Section 3) as well from from about 40 years of daily observations (Section 4). The nature of LF 'internal' variability simulated by the GCM is investigated in Section 5 and using a nonlinear dynamical model it is indicated that a modulation of ISO's by the annual cycle could be responsible for the internal LF variability simulated by the GCM. The multi-scale interactions through which the vigorous monsoon ISO's result in LF variability of the observed seasonal mean monsoon is also illustrated in this section. The results are summerized in Section 6.

2. Model and Data used

For the purpose of estimating predictability of the monsoon, we have used a three dimensional model of the atmosphere , an atmospheric general circulation model (AGCM) developed at the Geophysical Fluid Dynamics Laboratory (GFDL). The basic fluid dynamical equations of the model are solved using spectral element method (Gordon and Stern 1982). We carried out two long integrations with a version of the model that has rhomboidal 30 horizontal resolution (30 waves in the east-west direction and 30 associated Legendre functions in the north-south direction) and 14 unevenly spaced vertical levels. The horizontal resolution amounts to approximately 3.73 longitude by 2.25 latitude. The physical processes such as radiation (incoming short wave solar and outgoing long wave terrestrial radiation), dry and moist convection , boundary layer processes and ground hydrology are all parameterized (Gordon and Stern, 1982; Broccoli and Manabe, 1992; Goswami, 1998). At the lower boundary, surface temperature is prescribed over the ocean while it is determined from the prognostic hydrology model over land. A control integration (CTL-run) was carried out with the model in which monthly mean SST was prescribed from observations (Reynolds and Smith, 1994) for a period of 15 years (1979-1993). The observed SST has slow variations associated with the El Nino and Southern Oscillations (ENSO). These slowly varying boundary forcing induce slow 'external' variations of the model climate. Thus, simulations from this integration contains 'internal' as well as 'external' variability. A second sensitivity experiment, called FXSST-run , was carried out for 20 years in which prescribed SST had no interannual variations. In this run, long term mean SST annual cycle was prescribed at each grid point and was repeated every year. Since solar forcing is also fixed (i.e. no interannual variations), this run does not have any external interannual forcing. Therefore, any interannual variations simulated by the model in this experiment must arise from internal dynamics of the atmosphere and would give us an estimate of 'internal' interannual variance.

In order to make an estimate of predictability from observations, we use daily 850 hPa winds from NCEP/NCAR reanalysis for 33 years (1965-1997). The NCEP/NCAR reanalysis is a research quality product that uses an analysis system that is kept fixed throughout the reanalysis period and utilizes all available data. The data assimilation and forecast model used in the analysis system has horizontal resolution of T62 and 28 vertical levels. Details about the NCEP/NCAR reanalysis is available in Kalnay et al.(1996)and Kistler et al. (2001). In addition to the circulation data just mentioned, we also use satellite derived daily outgoing long wave radiation (OLR) data (Liebmann and Smith, 1996) for 23 years (1979-2001). The OLR data is a proxy for moist convection in the tropical regions. Rainfall estimate from CMAP (Climate Prediction Center's Merged Precipitation Analysis) is also used to study the clustering of synoptic systems by the monsoon ISO's. The CMAP produces pentad and monthly global analysis of precipitation in which observations from rain gauge are merged with precipitation estimates from several satellite based algorithms (Xie and Arkin, 1996). The random errors associated with different satellite products are minimized by using a linear combination of the satellite estimates with weights that are inversely proportional to known errors associated with each product.

3. Estimate of Predictability from an AGCM

Estimate of predictability of the Indian summer monsoon by an AGCM depends on estimates of total interannual variance and internal interannual variance of the Indian monsoon by the AGCM. For these estimates of variance to be reliable, the seasonal mean monsoon climate simulated by the AGCM should be realistic. The fidelity of the AGCM in simulation of the observed monsoon climate is shown in Fig.1.2 where observed

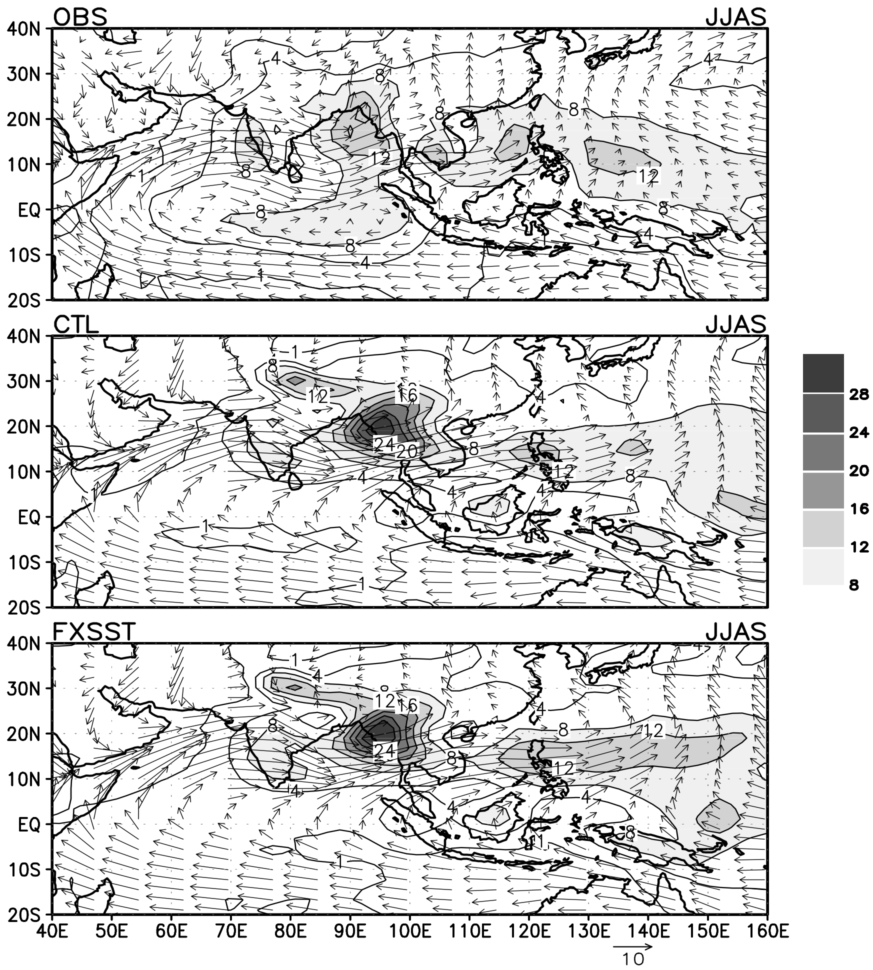

Figure 1.2. Long term mean wind vectors at 850 hPa and precipitation (shaded) averaged over June-September from observations (OBS), from the control run (CTL) and from fixed SST run (FXSST). Unit of precipitation is $mm\ day^{-1}$ and that for winds is $m\ s^{-1}$. Unit vector for winds is shown at the bottom.

climatological mean 850 hPa winds (from NCEP/NCAR reanalysis) and precipitation (Xie and Arkin, 1996) averaged during June to September (JJAS) are compared with those simulated by the AGCM in the CTL-run as well as in the FXSST-run. As may be expected, the climatological mean climate in the CTL-run and in the FXSST-run are almost identical. The simulation of precipitation over the Indian continent , south China Sea and western Pacific are quite reasonable. However, the model is deficient in simulating the secondary maximum in precipitation over the equatorial Indian Ocean. Most AGCM's have difficulty in simulating the observed precipitation over the continent correctly (Gadgil and Sajani, 1998). This AGCM is one of the few AGCM's that simulates the continental precipitation reasonably well. Thus, the estimate of interannual variance of precipitation over the Indian monsoon region may be considered reasonable. Monthly mean anomalies are constructed as deviation of simulated monthly means from long term annual cycle of simulations at each grid point for both CTL-run as well as FXSST-run.

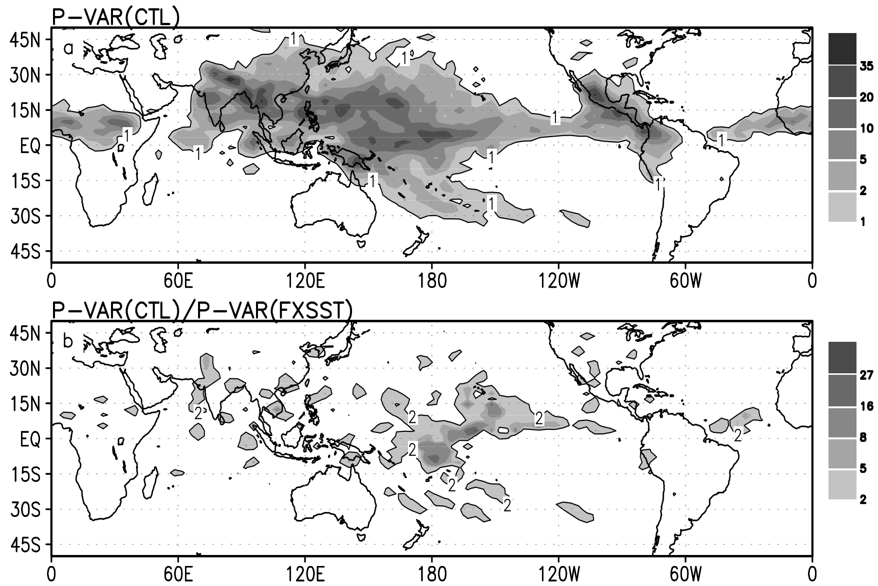

Figure 1.3. (Top) Variance of monthly mean precipitation anomaly ($(mm\ day^{-1})^2$) during northern summer (June-September) from 15 year simulation of the CTL-run. (Bottom) Ratio of variance between monthly mean precipitation anomaly during northern summer from the CTL-run and that from the FXSST run.

Monthly anomalies of June, July, August and September (JJAS) for all years are collected. Interannual variance of precipitation anomalies from the CTL-run for the summer monsoon season (JJAS) is shown in Fig.1.3a while ratio between the variance from CTL-run and FXSST-run is shown in Fig.1.3b. Since the variance of the CTL-run is a combination of boundary forced 'external' and 'internal' variances, while that from the FXSST-run is a measure of 'internal' variance, regions with a ratio of less than 2 indicates regions where the 'internal' variance is comparable or larger than the 'external' variance. The predictability is high over the equatorial central and eastern Pacific where the ratio is large and significant. The predictability is poor over the Asian monsoon regions where the ratio is barely two or less than two. In fact, with the degrees of freedom involved, the ratio of variance should be greater than 2.5 to be statistically significant. Thus, monthly mean precipitation over the Asian monsoon region during northern summer seems unpredictable. The distribution of ratio of variance of the seasonal mean precipitation during the northern summer was also calculated and was found to be very similar to Fig.1.3b.

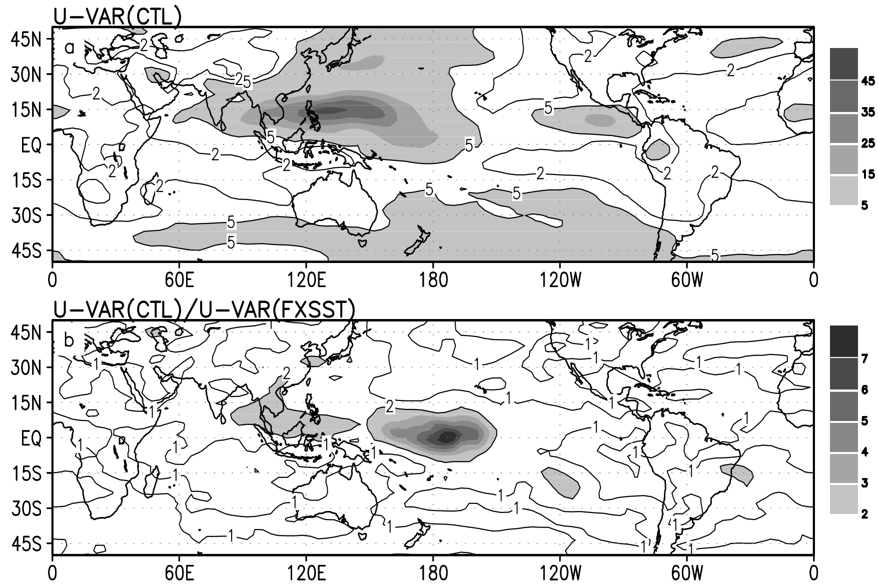

Figure 1.4. Same as (3) but for zonal winds at 860 hPa model level. Unit of variance of wind is $(mm\ day^{-1})^2$.

To supplement the predictability estimate for precipitation, similar estimate was made for for east-west component of wind (zonal wind) at a lower atmospheric level (860 hPa level of the model atmosphere) and is shown in Fig.1.4. Consistent with the ratio of variance for precipitation, the ratio of variance for zonal winds at 860 hPa is also less than 2 over the Asian monsoon region. The distribution of ratio of variance of the seasonal mean zonal winds at 860 hPa during the northern summer was also calculated and was found to be very similar to Fig.1.4b. Therefore, the monthly mean and seasonal mean circulation as well as precipitation anomalies seem to have poor predictability over the Asian monsoon region.

4. Estimate of Predictability from Observations

While it is relatively easy to estimate the 'internal' variability in an AGCM by artificially suppressing all external interannual forcing, it is not so simple to separate the internal component of variability from only one ensemble of observed data. Some assumptions invariably need to be made. We separate the 'internal' and 'external' component of interannual variance using the following hypothesis. The main interannual external forcing is the slowly varying boundary forcing associated with the ENSO SST variations. Since the time scale of ENSO SST variability is much longer (3-4 years to decadal) than the annual cycle, this forcing essentially results in a modulation of the annual cycle. The annual cycle of each field at each grid point for each year of observations is constructed as sum of the annual mean and the first three harmonics. An example of daily zonal winds at 850 hPa over the Bay of Bengal together with its annual cycle (thick line) for the year 1995 is shown (thin line) in Fig.1.5a. The variation of the annual cycle at the same point for five years is shown in Fig.1.5b. Significant interannual variation of the annual cycle is evident.

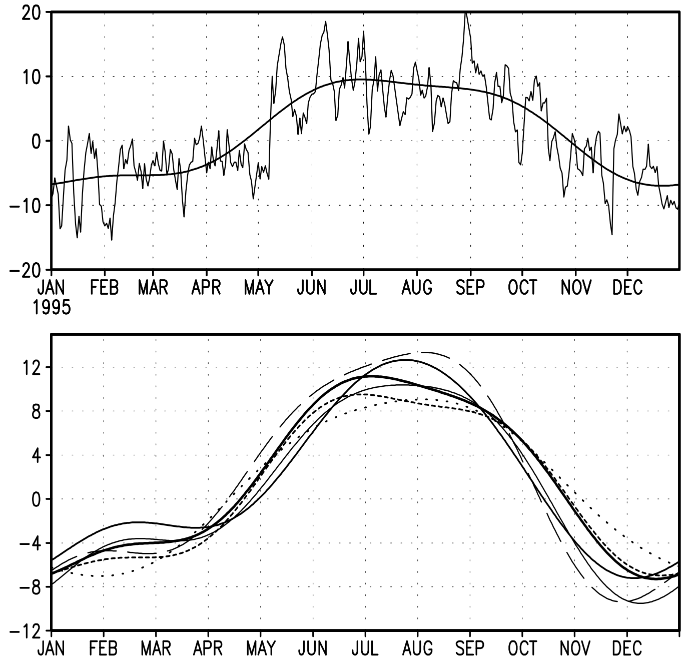

Figure 1.5. (Top) Daily 850 hPa zonal winds ($m\ s^{-1}$) at 90E, 15N for the year 1995 (thin line). The annual cycle is also shown (thick line). (Bottom) The annual cycles for five years are plotted illustrating the interannual variability.

A long term mean (climatological mean) annual cycle is constructed as average of annual cycles of all available years. Deviation of individual years annual cycle from the climatological annual cycle represents 'external' anomalies. Monthly mean of the 'external' anomalies for all years are created. The deviation of daily observations from the annual cycle of individual year represents 'internal' anomalies. Monthly means of the 'internal' anomalies for all years are also created.

The variance of 'external' and 'internal' anomalies of zonal winds at 850 hPa for the JJAS months are calculated based on 33 years of observations and shown in Fig.1.6b and Fig.1.6c and the ratio between the total variance and 'internal' variance is shown in Fig.1.6a. It may be noted that the external influence is weak and 'internal' variance largest over the Asian monsoon region leading to a ratio that is less than 2. Similar 'external' and 'internal' variances for OLR are shown in Fig.1.7b and Fig.1.7c while the ratio of the total and internal variances is shown in Fig.1.7a. Again we note that the ratio is less than 2 over the Asian monsoon region.

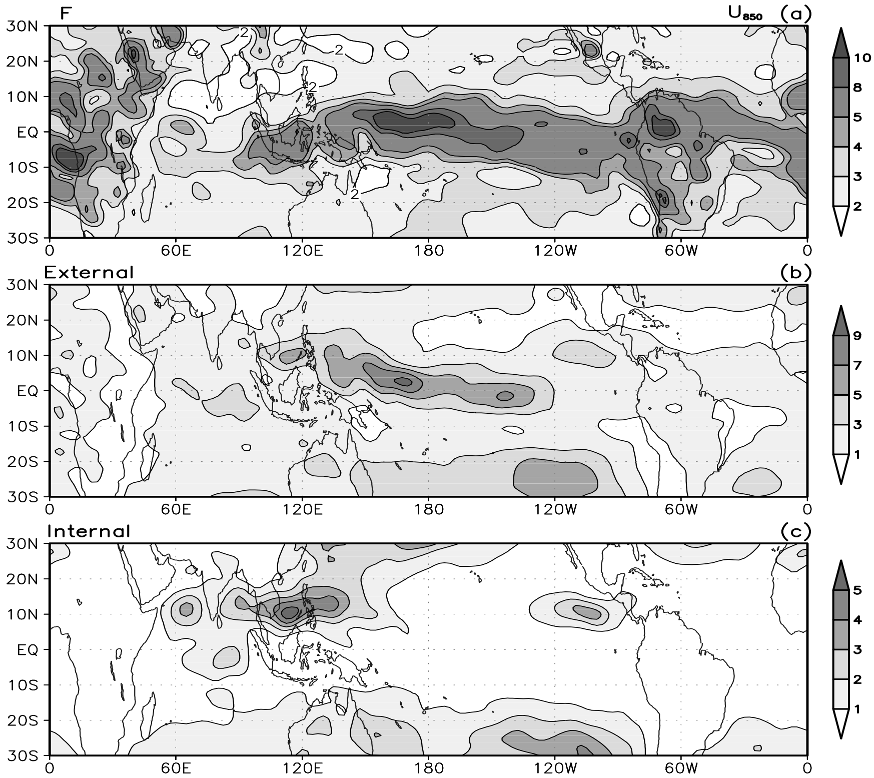

Figure 1.6. (a) Ratio between total variance ('external' +'internal') and 'internal' variance during northern summer (June-August) for zonal winds at 850 hPa. Spatial distribution of (b) 'external' and 'internal' components of the variance $(m\ s^{-1})^2$.

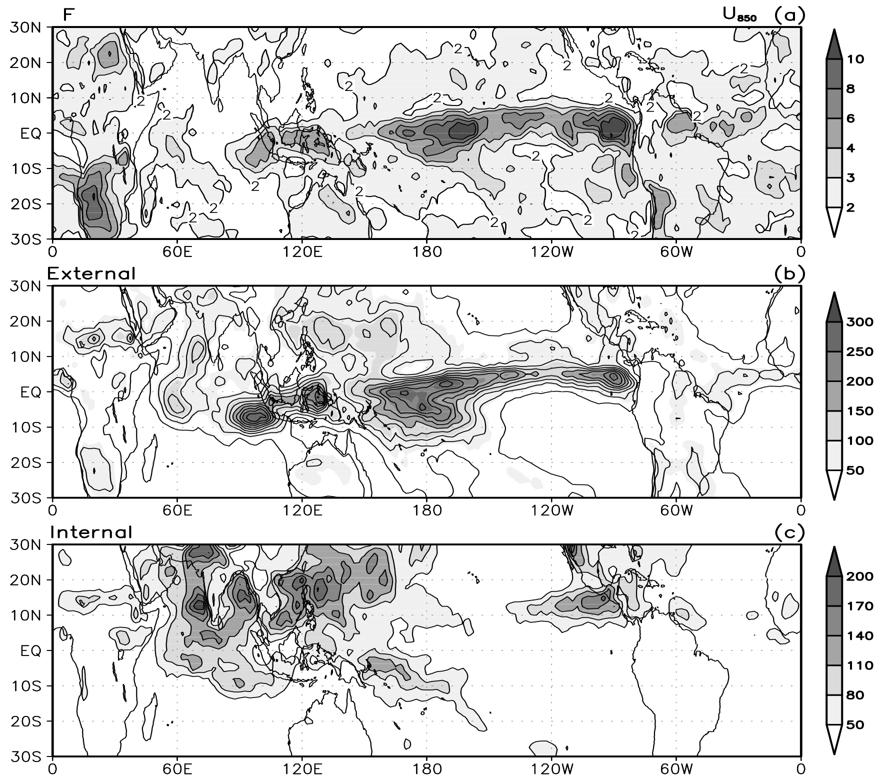

Figure 1.7. Same as Fig.6 but for OLR. Unit of variance for OLR is $(W\ m^{-2})^2$.

Thus, the estimates of predictability of the Asian monsoon from an AGCM are consistent with those obtained from observations. Both the estimates indicate that the 'internal' variability in this region is comparable to or larger than the 'external' variability (the signal being comparable to the 'noise'), seriously limiting the predictability of the Asian monsoon. At the same time it is also noted that both circulation and precipitation have high degree of predictability over the equatorial Pacific consistent with many other previous modelling studies.

The results of estimating predictability of monthly mean summer climate was extended to seasonal mean summer climate (Ajaya Mohan and Goswami, 2003) and it was shown that the main conclusion remains the same with seasonal climate as well. It may be noted that the 'internal' variance associated with interannual variability of the seasonal climate could not be estimated by the method described above and a slightly different approach need to be adopted.

5. Scale Interactions and 'Internal' LF Variability

What is responsible for generating significant interannual variability in the absence of any interannually varying external forcing over the Asian monsoon region? In this section, we attempt to gain insight towards the origin of 'internal' LF variability in this region. We note that Asian monsoon region is rather unique in the tropics for several reasons. This is a region where the amplitude of the annual cycle is the largest. The existence of the Himalayan mountains and the Indian land mass to the north of warm waters of the Indian Ocean is also unique resulting in the largest northward migration of the rain band (inter tropical convergence zone, ITCZ). This unique geophysical situation is also responsible for spawning vigorous northward propagating monsoon ISO's (Sikka and Gadgil, 1980; Yasunari, 1979, 1981). We propose that the monsoon ISO's play a key role in producing the 'internal' LF variability in this region through multi-scale interactions involving synoptic activity (lows and depressions) on one hand and the annual cycle on the other hand. The temporal and spatial characteristics of the monsoon ISO's have been studied extensively over the last three decades. The westward propagating 10-20 day mode (Krishnamurti and Bhalme, 1976; Krishnamurti and Ardunay, 1980) and the northward propagating 30-60 day mode (Yasunari, 1979; Sikka and Gadgil, 1980; Goswami and Ajayamohan, 2001a) are convectively coupled and could be seen in most circulation parameters as well as in precipitation. Proper phase relationship between the two modes manifest in the active (rainy spells) and break (dry spells) phases within the monsoon season(Goswami et al., 1998, 2003)

The seminal role of the monsoon ISO in producing the observed 'internal' variability could be seen from the fact that almost all the internal variance shown in Fig.1.6c and Fig.1.7c is due to the monsoon ISO's. To show this, the 'internal' variance was calculated after removing the high frequency component with period less than 10 days from the daily anomalies. The daily anomalies after removing the annual cycle was passed through a 10-90 day band pass Lanczos filter. Monthly mean 'internal' anomalies were calculated from the filtered data and 'internal' variance for JJAS was recalculated with the filtered monthly mean anomalies. The variance calculated in this manner represents the 'internal' variance arising from the ISO's. This is shown for zonal winds at 850 hPa in Fig.1.8b together with that from the full anomalies in Fig.1.8a. It is seen that almost all the 'internal' variance comes from the

ISO's. This was tested with OLR and other circulation parameters and found to be true in all cases.

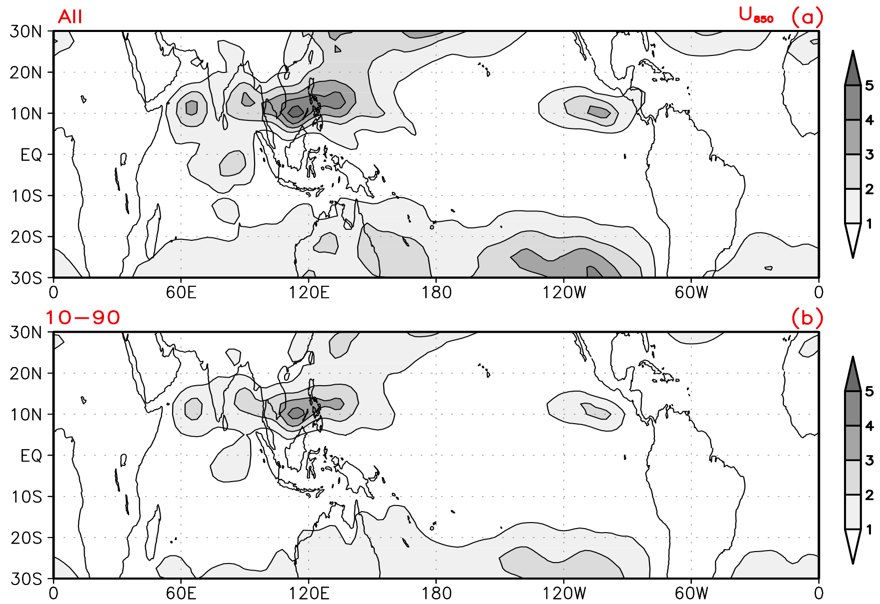

Figure 1.8. (a) Internal component of variance of zonal winds $(m\ s^{-1})^2$ at 850 hPa during June-July-August calculated from daily anomalies without filtering the synoptic events. (b) same as in (a) but based on 10-90 day filtered anomalies namely, after removing the synoptic events .

5.1 Nature of LF internal variability of the AGCM simulated monsoon

To gain some insight regarding the physical processes that lead to the internal LF variability, let us examine the nature of the LF variability simulated by the AGCM in the FXSST-run. To obtain a rough idea about the temporal scale of the LF internal variability, 5-month running mean of precipitation anomaly averaged between 140E-160E and 5S-5N, zonal winds at 860 hPa averaged between 50E-70E and 5S-5N and zonal winds at 170 hPa averaged between 140E-180E and 5S and 5N are plotted in Fig.1.9. A visual examination shows that an approximate quasi-biennial period is present in all three time series. The power spectra of the unfiltered time series (plotted on the right hand side of the figure) also confirm the observation that the statistically significant dominant LF mode has time scale between 20-30 months. It is found that the variations of precipitation, low level and upper level winds are strongly coupled for the 'internal' quasi-biennial mode and that the vertical structure is that of a first baroclinic mode (not shown).

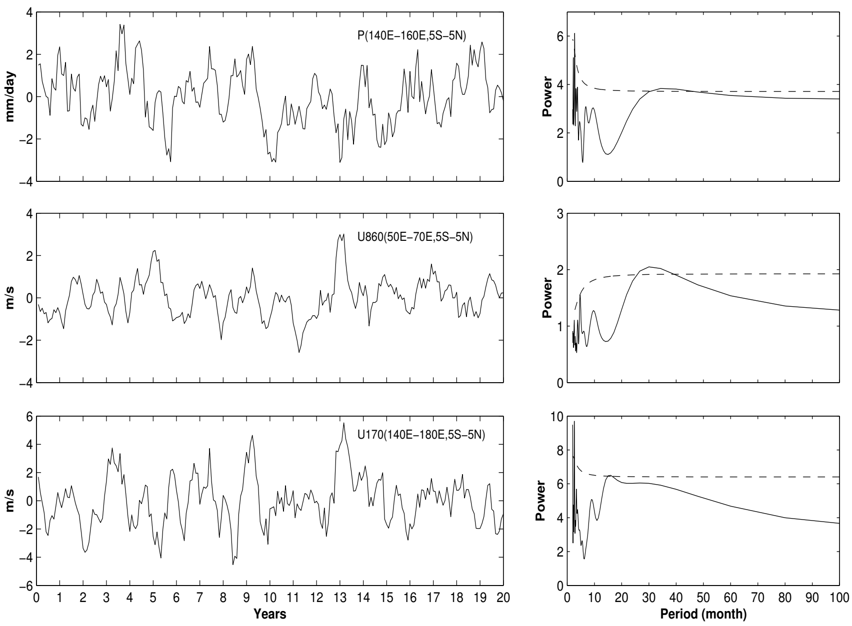

Figure 1.9. Evidence of existence of quasi-biennial mode of 'internal' variability in the AGCM simulated tropical climate. Five month running mean of precipitation anomalies averaged over (140E-160E, 5S-5N), zonal wind anomalies at 860hPa averaged over (50E-70E, 5S-5N) and zonal winds at 170hPa averaged over (140E-180E, 5S-5N) are shown on the left. The power spectra of unfiltered raw monthly anomalies of corresponding time series are shown on the right. 95% confidence limit for the spectra derived from theoretical red noise spectra based on lag-1 autocorrelation are also shown by dashed line.

How does the model atmosphere internally produces quasi-biennial oscillation? The model atmosphere has vigorous northward propagating ISO's with time scale of 30-50 days, like in observations. Nonlinear interaction between these ISO's and the annual cycle could give rise to some LF oscillations. The annually varying mean conditions act like a annually varying forcing for the ISO's. Could such nonlinear interactions give rise to a quasi biennial mode? To investigate this possibility, a simple nonlinear dynamical system model originally constructed by (Lorenz, 1984) to describe the general circulation of the atmosphere is used. The model is described by,

$$\begin{aligned} \dot{X} &= -Y^2 - Z^2 - aX + aF \\ \dot{Y} &= XY - bXZ - Y + G \\ \dot{Z} &= bXY + XZ - Z \end{aligned} \quad (1)$$

, where X may be interpreted as the zonal mean component while Y and Z may be considered as two wave components. The terms XY and XZ represent amplification of the waves through interaction with the mean flow and happens at the expense of the mean flow represented by the terms $-Y^2$ and $-Z^2$ in Eq.1. The terms -bXZ and bXY represent displacement of the waves by the mean flow. The linear terms represent mechanical and thermal damping. F is forcing for the zonally symmetric component like the solar forcing while G is forcing for the wave component like the land-ocean contrast. For fixed values of a, b and G , different values of the solar forcing F leads to solutions of the Eq.1 that varies from periodic solutions with different periods to chaotic or aperiodic solutions for some values of F. Our intention is that the temporal characteristics of fluctuations in the chaotic regime should be representative of that of the monsoon ISO. It is found that this could be achieved by scaling the time in Eq.(1) by a factor C(=0.57). The variables X,Y and Z, the parameter a and forcings F and G are also scaled appropriately. Using unscaled parameters, a=0.25,b=4.0,G=1.18, for F=7.99, the solution is quite aperiodic Fig.1.10a,b with dominant periods between 30-70 days (Fig.1.10c) in X and 10-20 days in Y (Fig.1.10d). The spectrum of oscillations represented by the model is characteristic of that of the monsoon ISO. The forcing F is then made to have an annual cycle like the solar forcing namely, $F = F_0 + F_1 Cos(2\pi t/T)$, with period T as one year. Taking F_0= 5.7 and F_1=2.6, the equations were integrated for more than 250 years. Time series for X and Y for a typical 10 year period and the corresponding spectra are shown in Fig.1.11. It is seen that modulation of the intraseasonal oscillations by the annual cycle has resulted in a strong quasi-biennial oscillation in both X and Y. The system seems to go to one attractor in one year characterized by a low mean X and high mean Y, both with very low amplitude of fluctuations while it goes to another attractor in the next year with high mean X and low mean Y, both with high amplitude oscillations. Thus, if the intraseasonal oscillations are vigorous and nonlinear and the annual cycle of the mean flow is strong, interaction between the ISO's and the annual cycle could result in an 'internal' quasi-biennial oscillation. The observed 'internal' quasi-biennial oscillation in the AGCM simulated climate may be due to such a mechanism.

5.2 Origin of 'internal' LF variability in observations.

The mechanism proposed above for generating LF internal variability assumes that the nonlinear interactions amongst the ISO's is strong. Is

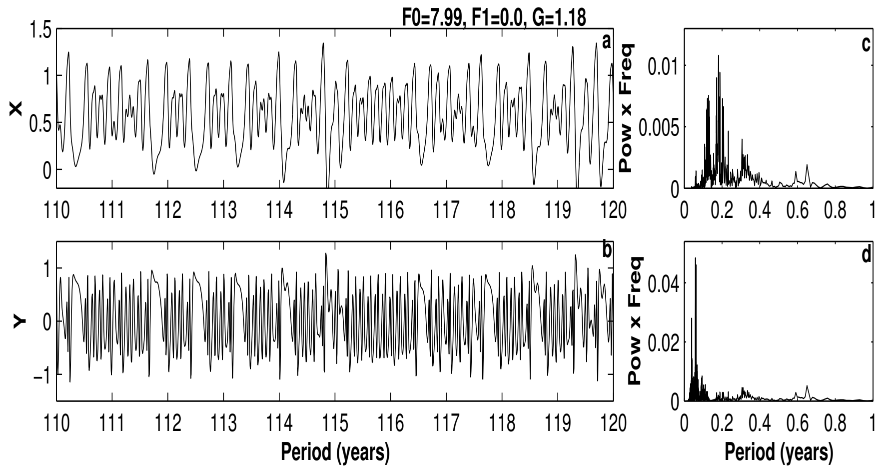

Figure 1.10. Time series of X and Y for constant forcing F_0=7.99 , F_1=0.0 and G=1.18 (left) for a typical 10 year period from a 200 year simulation with corresponding spectra (right). Power spectrum is plotted as power multiplied by frequency versus period.

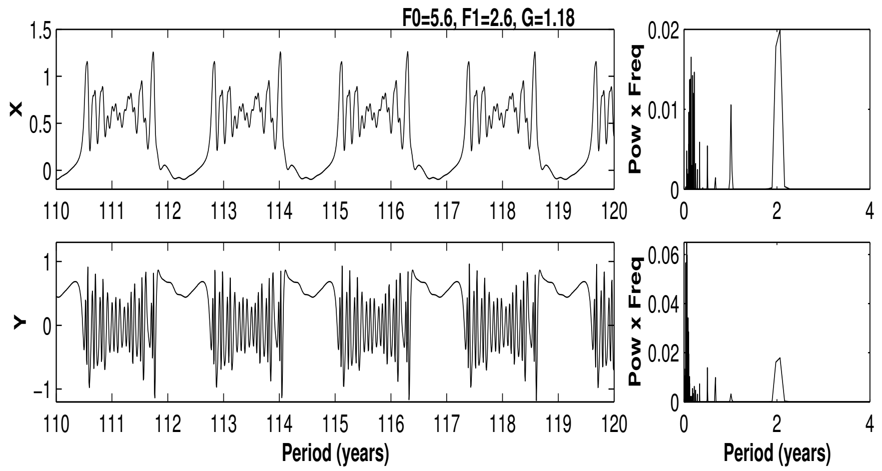

Figure 1.11. Same as Fig.10 but for an annually varying forcing, F_0=5.6, F_1=2.6 and G=1.18 that includes the chaotic regime shown in Fig.10.

it really strong for the tropical ISO's? The characteristic length scale associated with monsoon ISO's is approximately 10,000 km and typical velocity scale is 5-10 m/s. For such systems, the non-dimensional equatorial Rossby number $R_0 = U/\beta L^2$, (with β being the meridional gradient of the Coriolis parameter) is much less than one indicating that advective nonlinearity for these systems is rather weak. Therefore, we have to look for other linear mechanisms through which the ISO's could give rise to interannual variability of the monsoon.

How could the monsoon ISO's give rise to interannual variability of the seasonal mean monsoon? We recall that the seasonal mean monsoon precipitation is characterized by a strong band of precipitation over the monsoon trough region and a secondary precipitation band in the equatorial eastern IO Fig.1.2a. The mean flow at low level is characterized by the cross equatorial flow, the low-level jet and the large scale low level cyclonic vorticity or the monsoon trough Fig.1.2a. The upper level mean flow also has similar large spatial scale characterized by the monsoon easterly jet (not shown). The ISO's have characteristic time scale of 10-20 days and 30-60 days. For the ISO's to influence the mean monsoon in a linear sense, the collective effect of the ISO fluctuations within the season should be either to enhance or to weaken the large scale monsoon flow shown in Fig.1.2a. The ISO's could do this *only if* the spatial scale of the ISO's has large scale structure similar to that of the seasonal mean flow. If the spatial scale of the ISO's is much smaller than that of the mean monsoon flow, the strengthening and weakening in different parts of the mean flow would result in no net strengthening or weakening of the mean flow. Even if the spatial structure of the ISO's is similar to that of the seasonal mean, they would not result in any net strengthening or weakening if the frequency of occurrence of the positive and negative phases of the ISO are the same. Thus, if the spatial scale of the ISO's is similar to that of the seasonal mean and if the frequency of occurrence of positive (active) and negative (break) phases are different in different years, the ISO's could result in an interannual variability of the monsoon.

To test this hypothesis, we first examine the spatial structure of the monsoon ISO. For this purpose a compositing technique is used. A reference time series is constructed with the 30-60 day filtered zonal wind anomalies at 850 hPa at 90E and 15N from June 1 to September 30 of each year for 20 years. The time series is normalized by its own standard deviation. Normalized index greater (lesser) than +1 (-1) represents strong (weak) ISO conditions. The strong and weak ISO conditions are also known as active and break phases of the monsoon. A composite (average) of all active and break days over the 20 summer seasons (1979-1998) for zonal and meridional wind anomalies is created. The composited vector wind anomalies for active and break conditions are shown in Fig.1.12a,b together with associated relative vorticity anomalies. For the same dates, composites of OLR anomalies corresponding to active and break conditions are constructed based on the same period and plotted in Fig.1.12c,d. It may be recalled that low OLR represents deep clouds. Thus, negative (positive) OLR anomaly represents increase (decrease) in convection. We note Fig.1.12a,b that the spatial structure of the ISO wind anomalies has a large scale similar to that of the seasonal mean Fig.1.2a and strengthens (weakens) the seasonal mean during active (break) phases. It may also be noted that circulation anomalies associated with active (break) condition strengthens (weakens) the cyclonic vorticity in the monsoon trough region and weakens (strengthens) the vorticity between 10S and 10N. Note that positive (negative) relative vorticity in the southern hemisphere represents anticyclonic (cyclonic) vorticity. The OLR anomalies Fig.1.12c,d show a bimodal meridional structure with active (break) conditions characterized by enhancement of convection (precipitation) in the monsoon trough region and decrease (increase) in convection (precipitation) over the equatorial precipitation zone.

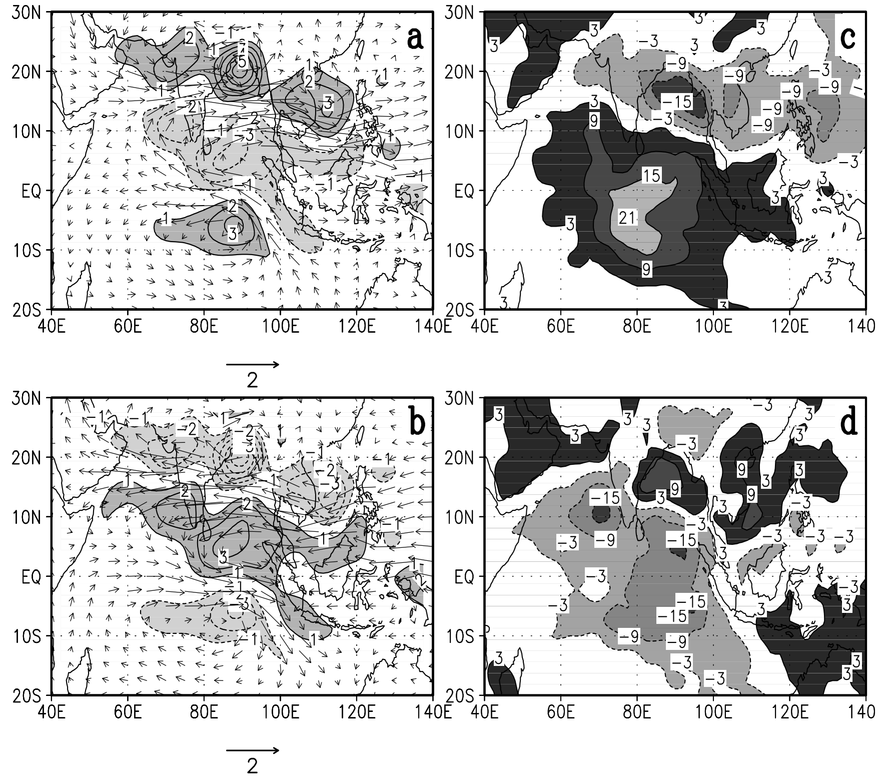

Figure 1.12. Mean structure of extreme phases of monsoon ISO. (a) Composite of all active phases in 20 summer seasons of winds at 850 hPa ($m\ s^{-1}$). Corresponding relative vorticity ($10^{-6}\ s^{-1}$) are shaded. (b) same as (a) but for all break cases. Corresponding composite of OLR anomalies ($W\ m^{-2}$) are shown in (c) and (d).

The similarity in spatial structure of the intraseasonal and interannual variability is further illustrated in Fig.1.13 where we plot the dominant empirical orthogonal function (EOF) of intraseasonal wind anomalies at 850 hPa from daily data for 20 summer seasons (1979-1998) together with the first EOF of seasonal mean winds (JJAS) for a period of 40 years (1959-1998). The dominant pattern of intraseasonal variability of wind anomalies at low level show high degree of similarity with the dominant pattern of interannual variability of winds at the same level.

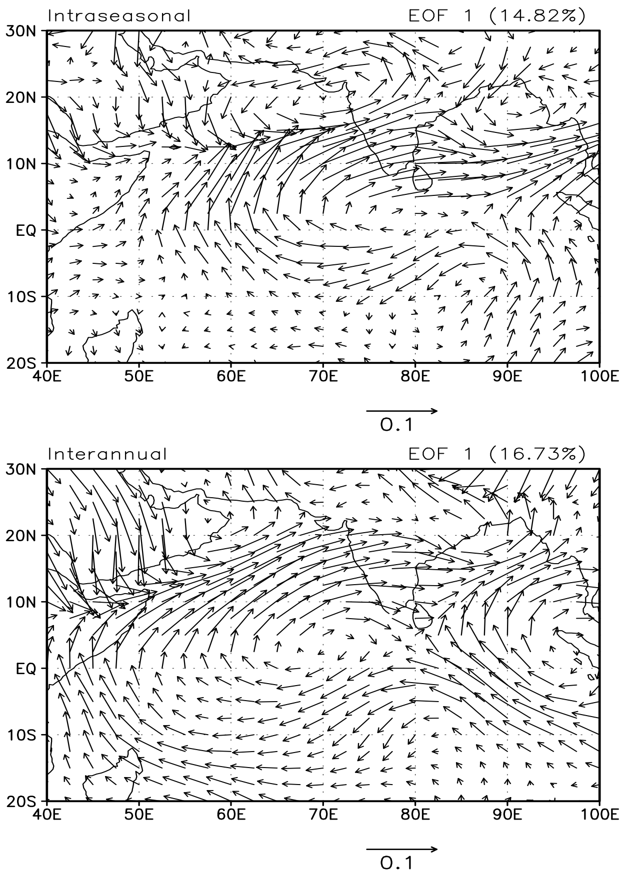

Figure 1.13. Similarity between the dominant mode of intraseasonal variability and interannual variability of seasonal mean. (Top) The dominant empirical orthogonal function (EOF) of 10-90 day filtered daily 850 hPa winds for 20 summer seasons (June 1 to September 30). (Bottom) The dominant EOF of interannual variability of the seasonal mean winds at 850 hPa based on 40 summer seasons. Unit of the EOF's is arbitrary.

Having established that the spatial pattern of intraseasonal oscillations is similar to that of the seasonal mean and its interannual variability, the difference in frequency of occurrence of active and break phases of the monsoon intraseasonal oscillations in different years is investigated. If the integrated influence of active conditions is larger than that of break conditions in a given season, the monsoon in that year would be stronger than normal and vice versa. Therefore, in a strong (weak) monsoon year, we expect probability density of occurrence of active (break) condition to be higher than its counterpart. Using OLR and circulation data between 1974 and 1997, the ISO's are described by the phase space mapped by the first two combined EOF's of 850 hPa winds and OLR. Six strong monsoon years (1975, 1978, 1983, 1988, 1990, 1994) and six weak monsoon years (1974, 1979, 1982, 1985, 1986, 1987) are selected based on rainfall over the Indian continent being more than 0.5 s.d above normal or below normal. The two dimensional probability density function (pdf) in the phase space described by the first two principal components (PC's) is estimated using a Gaussian kernel estimator (Kimoto and Ghil, 1993) and shown in Fig.1.14 for the strong monsoon years, the weak monsoon years and all the years taken together. When all the years are taken together , the pdf seems to be nearly a Gaussian. However, for both strong and weak monsoon years , the pdf is non-Gaussian. To test the statistical significance of the maxima of the calculated pdf's, 1000 random sets of PC1 and PC2 time series were created having the same variance and lag-1 autocorrelation and pdf's were again created. The shading in Fig.1.14a,b indicate regions where the observed pdf is significantly larger than the random ones with 90% confidence level. Thus, the maxima in Fig.1.14a,b appear to be statistically significant. The spatial pattern for the most probable state is reconstructed by noting the values of PC1 and PC2 from Fig.1.14 and using the corresponding EOF patterns and is shown in Fig.1.15 for all the three cases. The most probable vorticity and OLR patterns in strong monsoon years are that of an active condition Fig.1.12a,c while that during weak monsoon years corresponds to that of a break condition (Fig.1.12b,d). However, if all years are combined , transition from active to break (or break to active) seems to be the dominant pattern (Fig.1.15c). Thus, frequency of occurrence of active (break) phases in a particular monsoon season seems to modulate the intensity of seasonal mean monsoon rainfall.

How do the changes in the frequency of occurrence of phases of monsoon ISO's modulate the seasonal mean rainfall? The primary rain producing synoptic systems during the monsoon season are the lows and depressions. The lows and depressions are essentially shear instability energized by latent heat released due to convection. As we have noted in Fig.1.12a,b, the monsoon ISO's intensifies (weakens) the mean monsoon flow during active (break) phase and strengthens (weakens) the cyclonic vorticity in the monsoon trough. The enhancement of merid-

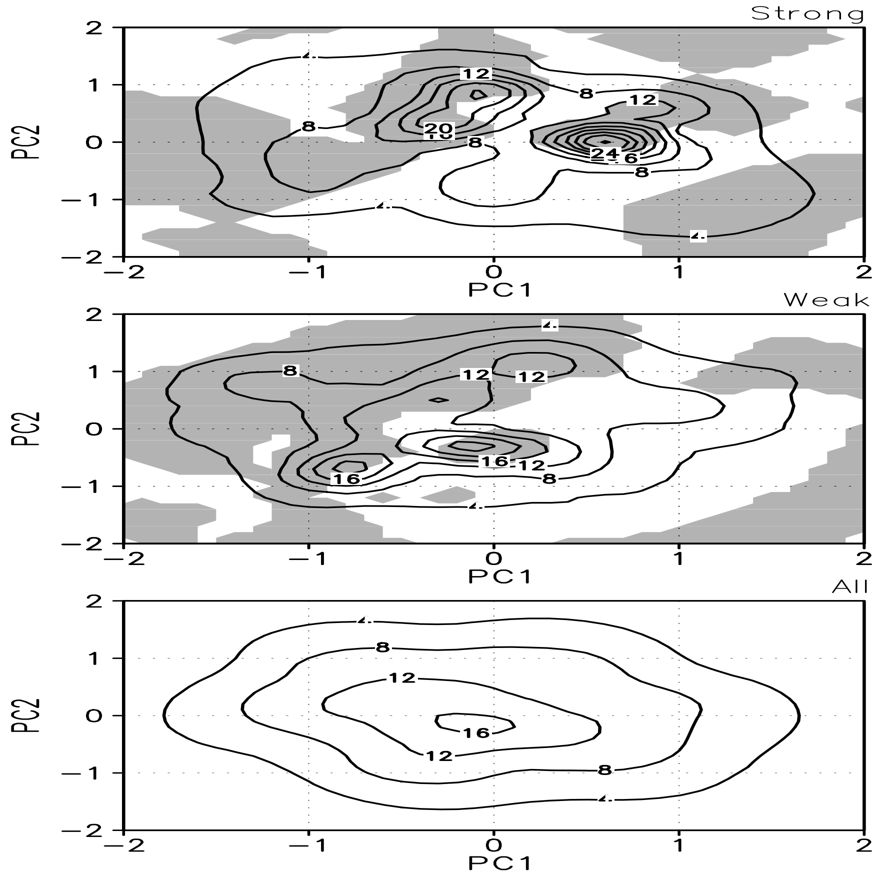

Figure 1.14. Two dimensional pdf's of ISO state vector represented by the two dominant combined EOF's of relative vorticity at 850 hPa and OLR. The EOFs are calculated with 10-90 filtered fields between June 1 and September 30 for 6 strong monsoon years, 6 weak monsoon years and all 23 years (1974-1997) and pdf's are calculated from the two principal component (PC) time series. The pdf estimates are multiplied by a factor of 100. The shading represents regions where the pdf estimates are statistically significant with 95% confidence level. The origin of the plots represent a very weak state representing transition from active to break condition or vice versa.

ional shear during active condition enhances the potential for instability and enhancement of low level cyclonic vorticity enhances frictional convergence of moisture and facilitates organized convection. Both these processes increases the potential for cyclogenesis. Similarly, modulation of the large scale flow by the ISO's during break conditions inhibits cyclogenesis. Thus, the ISO's could cluster the synoptic disturbances in space and time.

To investigate whether the ISO's indeed result in clustering of the synoptic disturbances, genesis dates and tracks of lows and depressions

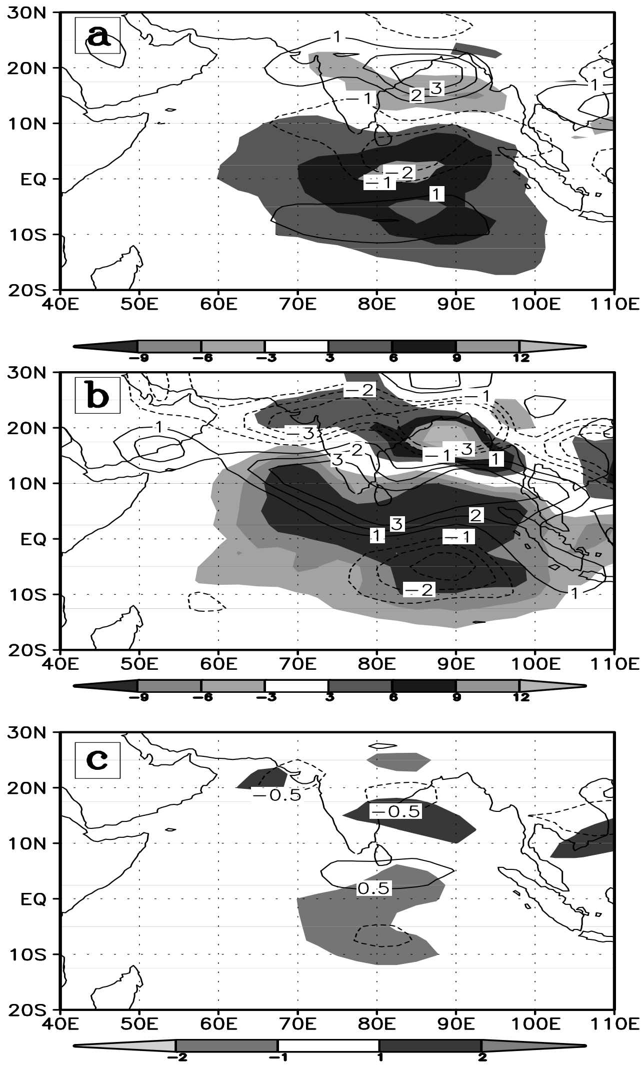

Figure 1.15. Spatial structure associated with the most probable patterns of intraseasonal variability during (a) strong monsoon years, (b) weak monsoon years and (c) all years combined. The vorticity pattern is shown in contours ($10^{-6}\ s^{-1}$) while the OLR pattern is shown in shading ($W\ m^{-2}$) .

during June-September during a period of 40 years (1954-1993) over the Indian monsoon region were collected. Lows and depressions are collectively called low pressure systems (LPS). The data for the first 30 years (1954-1983) were carefully collected by Mooley and Shukla (1989) from Daily Weather Reports and annual summary of tracks of storms and depressions published by Indian Meteorology Department (IMD).

The data for the last 10 years were collected by us from the summary of tracks of storms and depressions published every year by the India Meteorological Department. In order to examine the clustering of the synoptic disturbances by the ISO's, we need to characterize the ISO quantitatively. We noted earlier that the the monsoon ISO's are closely associated with fluctuations of relative vorticity at 850 hPa (Fig.1.12a,b). Therefore, we define an index of monsoon ISO activity (MISI) as 10-90 day filtered relative vorticity at 850 hPa averaged over 80E-95E and 12N-22N (Goswami et al., 2003). The index is normalized by its own s.d. Normalized MISI ¿ +1 represents active condition while MISI ¡ -1 represents break conditions. The frequency distribution of LPS as a function of the phase of the ISO is obtained by putting the genesis dates of all the LPS during the 40 year period into bins of MISI of size 0.25 (Fig.1.16,top). The frequency distribution is clearly skewed towards the positive MISI side with more than twice as many genesis occurring for MISI ¿0 compared to those occurring for MISI¡0. In particular, birth of a LPS is 3.5 time more likely in the active phase of the ISO (MISI¿+1) than in a break phase (MISI¡-1). The tracks of LPS occurring during active and break phases are plotted in the middle and bottom panel of Fig. 1.16. It is clear that the LPS is not only clustered in in time (Fig.1.16,top), they are highly clustered in space as well. Therefore, increased frequency of occurrence of active condition in a particular year results in significantly enhanced number of LPS formed in that year that are spatially largely confined to the monsoon trough area. The collective result of this is enhanced seasonal mean rainfall over Indian continent and a stronger than normal monsoon.

6. Conclusions

The physical basis for predictability of climate beyond the limit on deterministic predictability of weather (approximately two weeks) has been well established (Charney and Shukla, 1981; Shukla, 1981) based on realization that the climate is governed by slowly varying forcing either external or arising from slow coupled ocean-atmosphere interactions. However, the atmosphere can generate certain amount of internal LF variability through a number of internal feedbacks that would remain unpredictable. The predictability of climate would depend on relative contribution of internal and external LF variability to the total interannual variability. Advances in climate modeling has demonstrated that tropical climate has much higher predictability compared to extra-tropical climate. However, the Indian summer monsoon within the tropics remains to be the most difficult system to simulate and predict. In

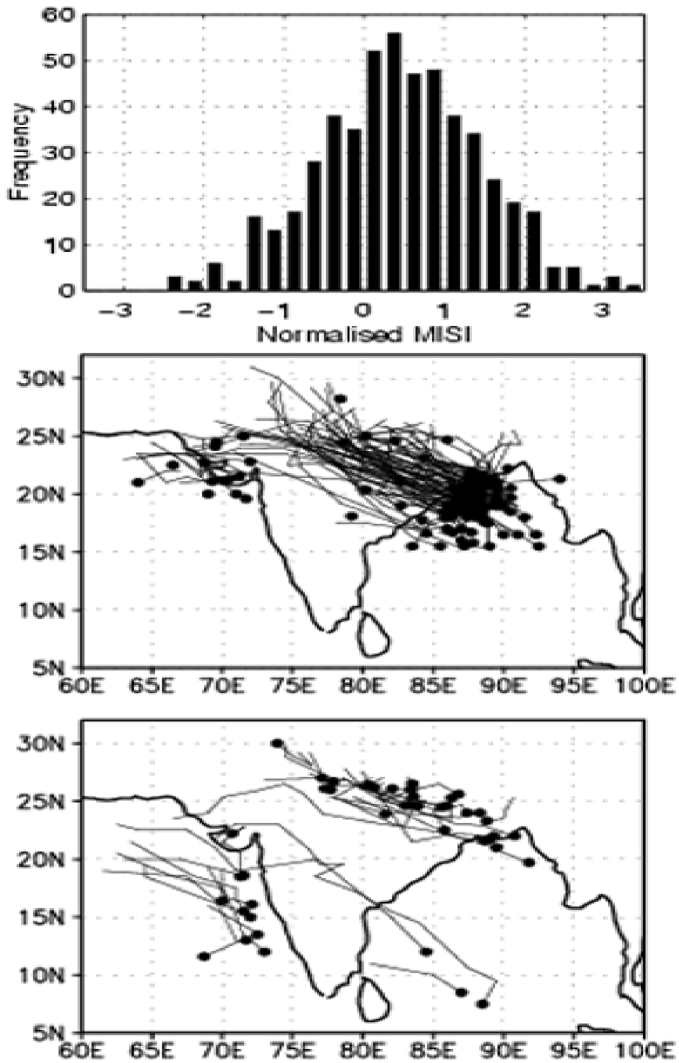

Figure 1.16. Clustering of synoptic activity by the monsoon ISO. (top) Frequency distribution of low pressure systems (LPS, lows and depressions) as a function of the normalized monsoon intraseasonal index (MISI) based on 40 years of data on LPS genesis and corresponding MISI time series . (middle) Tracks of LPS during active phases (MISI ¿ +1) and (bottom) tracks of LPS during break phases (MISI ¡ -1).

this study, an attempt has been made to unravel the underlying reasons responsible for limited predictability of Indian summer monsoon climate.

In order to quantify the problem, an estimate of predictability of Indian summer monsoon is made using an atmospheric general circulation model (AGCM) as well as from about 40 years of daily circulation data.

Having devised methods to estimate the 'internal' interannual variability in the AGCM as well as from observations, the ratio between total and 'internal' interannual variability is found to be less than 2 over the Indian monsoon region in the AGCM simulations as well as in observations. This indicates that more than 50% of interannual variability of the Indian summer monsoon is governed by 'internal' dynamics and hence are unpredictable.

The origin of the 'internal' variability in the AGCM and in observations is then investigated. It is shown that the monsoon ISO's with time scales between 10-70 days play a seminal role in generating the observed LF 'internal' variability through multi-scale interactions with synoptic disturbances on one hand and the annual cycle on the other. The nature of these scale interactions leading to LF 'internal' variability is illustrated. It is shown that a modulation of nonlinearly interacting ISO's by the annual cycle of forcing can give rise to a significant quasi-biennial 'internal' oscillation. The possibility of such a mechanism to be responsible for the quasi-biennial oscillation simulated the AGCM is indicated. However, it is pointed out that nonlinearity associated with the observed monsoon ISO's may be rather weak. Therefore, a linear mechanism through which ISO's could influence the seasonal mean and its interannual variability is sought and identified. The mechanism works as follows. Based on an analysis of more than 20 years of daily data, it is first established that the spatial structure of two extreme phases of the monsoon ISO , namely the active and break phases, is similar to that of the seasonal mean, strengthening the mean in one phase while weakening it in the other. It is further shown that the spatial structures of the dominant intraseasonal mode and interannual mode of monsoon variability are very similar. Hence, a higher than normal frequency of occurrence of active (break) phases in a season could lead to a stronger (weaker) than normal monsoon. This is then shown that strong (weak) Indian monsoons are indeed associated with higher probability density of occurrence of active (break) condition, establishing that to a large extent the interannual variability of Indian monsoon is controlled by frequency of occurrence of active/break cycles. It is further shown that the monsoon ISO's also cause strong spatial and temporal clustering of the synoptic disturbances. Monsoon ISO's influence the seasonal mean rainfall through changes in frequency distribution active or break conditions and by producing space-time clustering of lows and depressions.

The monsoon ISO's owe their origin to feedbacks between organized convection and large scale dynamics (Webster, 1983; Goswami and Shukla, 1984; Nanjundiah et al., 1992; Chatterjee and Goswami, 2004). Thus, they are essentially of 'internal' atmospheric origin. The fraction of interannual variability of the Indian monsoon accounted for by this process is therefore, sensitive to initial condition and hence unpredictable. The amplitude of 'externally' forced variability being rather weak over Indian monsoon region while that of the 'internal' variability generated by the ISO's is relatively large limits the predictability of the Indian summer monsoon. This fundamental reason will continue to make the long range prediction of seasonal mean monsoon a difficult and challenging problem. The challenge will be to find innovative method of bringing out the small predictable signal from the background of unpredictable noise of comparable amplitude.

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