MONSOON -ENSO RELATIONSHIPS : A NEW PARADIGM

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Invited submission to Special Issue of Adv. Atmos. Sciences

ABSTRACT

This article is partly a review and partly a new research paper on monsoon-ENSO relationship. The paper begins with a discussion of the basic relationship between the Indian monsoon and ENSO dating back to the work of Sir Gilbert Walker up to research results in more recent years. Various factors that may affect the monsoon-ENSO relationship, including regional coupled ocean-atmosphere processes, Eurasian snow cover, land-atmosphere hydrologic feedback, intraseasonal oscillation, biennial variability and inter-decadal variations, are discussed. The extreme complex and highly nonlinear nature of the monsoon-ENSO relationship is stressed. We find that for regional impacts on the monsoon, El Niño and La Niña. are far from simply mirror images of each other. These two polarities of ENSO can have strong or no impacts on monsoon anomalies depending on the strength of the intraseasonal oscillations and the phases of the inter-decadal variations. For the Asian-Australian monsoon (AAM) as a whole, the ENSO impact is effected through a east-west shift in the Walker Circulation. For rainfall anomalies over specific monsoon areas, regional processes play important roles in addition to the shift in the Walker Circulation. One of the key regional processes identified for the boreal summer monsoon is the anomalous West Pacific Anticyclone (WPA). This regional feature has similar signatures in interannual and intraseasonal time scales and appears to determine whether the monsoon-ENSO relationship is strong or weak in a given year. Another important regional feature includes a rainfall and SST dipole across the Indian Ocean, which may have strong impact on the austral summer monsoon. Results are shown indicating that monsoon surface wind forcings may induce a strong biennial signal in ENSO, and that strong monsoon-ENSO coupling may translate

into pronounced biennial variability in ENSO. Finally, a new paradigm is proposed for the study of monsoon variability. This paradigm provides a unified framework in which monsoon predictability, the role of regional vs. basin-scale processes, its relationship with different climate subsystems, and causes of secular changes in monsoon-ENSO relationship can be investigated.

1. Introduction

The word monsoon is derived from the Arabic word "Masaum" which means season. In monsoon regions, the change of season is accompanied by a reversal of the prevailing wind direction and abrupt changes in rainfall patterns. The most pronounced monsoon climate is found in the Asian-Australian region. Other regions that exhibit monsoonal characteristics include the maritime continent, western Africa, central America, southwestern North America, and eastern and northeastern South America. These regions are often devastated by severe droughts and floods caused by the strong year-to year-variability in monsoon rainfall. In this paper, we focus the discussion on the Asian-Australian Monsoon (AAM) and its relationship with the El Niño Southern Oscillation (ENSO).

During the summer of 1997, southern China was stricken by widespread flooding, while northern China was gripped by one of the driest season on record. In the summer 1998, a monsoon depression in Bengladesh devastated the country causing major floods in the Ganges and the Brahmaputra river, displacing over 30 million people, resulting in property and agricultural loss of over 3.4 billion US dollars. In the same summer, a flood of biblical proportion ravaged the Yangtze River basin and northeastern China, displacing over 220 million people, inflicting a huge economic loss of over 12 billion US dollars. Understanding and predicting AAM variability is therefore vitally important with immense payoff in societal benefits.

Scientists have long suspected that there is a connection between monsoon rainfall variability and various components of the global circulation system. Walker (1923, 1924) found that the Indian monsoon rainfall anomalies appeared to be foreshadowed by seasonal surface pressure variations over several "strategic" points far remote from India. Of the many planetary-scale patterns found by Walker, the most important is the Southern Oscillation (SO), which was described as " a swaying of pressure on a big scale .

backwards and forwards between the Pacific Ocean and the Indian Ocean". However, his effort to translate the monsoon-SO relationship to seasonal and interannual prediction of Indian monsoon rainfall was largely unsuccessful. Several decades later, Bjerknes (1969) first suggested that the SO as found by Walker is closely linked to the El Niño Bjerknes' work and subsequent research by others have led to the development of various empirical monsoon forecast schemes based on ENSO. However, results have been mixed, because even though ENSO may be important in influencing monsoon rainfall variability, there are large number of factors that may confound or limit monsoon predictability (Webster et al 1998).

Many previous studies of monsoon-ENSO relationship are focused on the impact of ENSO on the AAM. Very little has been said about how AAM can impact ENSO and other climate subsystems. Up to now, various monsoon-ENSO relationships have been established mostly based on monsoon indices derived from rainfall records in small regions (often biased by the need to separate into national or provincial boundaries) which are not necessarily representative of the entire AAM system. Therefore monsoon-ENSO relationship based on such indices may not be appropriate to describe relationship between ENSO and the entire monsoon system. In this paper, we will enunciate a new paradigm in which monsoon variability, monsoon-ENSO relationship and other contributing factors can be studied in a unified framework.

2. The basic relationship

A quantitative relationship between ENSO and Indian summer monsoon began to emerge in the 1980's (e.g., Rasmussen and Carpenter 1983, Shukla and Paolino 1983). However this relationship seems to have large decadal scale modulations, and to have weakened considerably in recent decades (see discussion in Section 4). Figure 1 shows the time series of all-Indian summer rainfall (June-September) from 1871 to 1998. Large interannual variability and interdecadal modulation of the amplitude of the anomalies are obvious. While relatively small anomalies are found in the decades of 1880-1890s, 1920-40s, and in the 1990s, much larger anomalies are found in the 1900-1920s, 1960-1980s. From Fig. 1, the following basic relationship can be drawn. *The Indian monsoon is* *generally below normal preceding the peak of a warm SST event (El Niño) and above normal preceding a cold event (La Niña).* However, there are warm or cold events that produce very weak signals or even anomalies of the opposite sign. Most important, a large number of major rainfall anomalies are not related to either El Niño or La Niña.

<Fig. 1 near here>

Table 1 summarizes the monsoon rainfall statistics in relationship to the occurrence of El Niño and La Niña for multi-decadal period, for all-India and for northern Australia. During the data period, out of the 53 events classified as below average, 24 events are associated with El Niño. Only 2 are associated with La Niña. For 71 above-average events, 4 belong to the El Niño group and 19 to the La Niña group. Altogether, El Niño explains less than 50% of the total below-average events and La Niña less than 30% of the above-normal events. For extreme events, the statistics shown in Table 1 convey the same message. Out of the 22 extremely deficient-rainfall events, 11 are associated with El Niño and only 2 are found in La Niña. Conversely, for extreme excessive-rainfall events, 7 out of 18 are found in La Niña, and none associated with El Niño. For northern Australia, the statistics are very similar. Obviously, the above relationship is far from perfect, but it is clear that in some fundamental way the AA-monsoon and ENSO are related.

	All India		Northern Australia	
Rainfall	Total	El Niño(La Niña)	Total	El Niño (La Niña)
Below average	53	24 (2)	49	20 (4)
Above average	71	4 (19)	58	5 (17)
Drought	22	11 (2)	18	9 (0)
Flood	18	0 (7)	17	2 (5)

Table 1 Rainfall anomaly statistics for All –India summer rainfall and Northern Australia summer rainfall, based on approximately 124 years of data (adopted from Webster et al 199~~9~~).
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3. Spatial Patterns

To understand the physical mechanism of the basic ENSO-monsoon relationship, we turn to the spatial distribution of rainfall and large-scale circulation anomalies associated with ENSO. Fig. 2 shows the seasonal climatologies and composites of seasonal mean anomalies of rainfall and surface wind over the AA-monsoon region for December-February-January (DJF) and June-July-August (JJA) respectively. The anomalies are shown as the difference between composites of El Niño and La Niña. Climatologically, the boreal summer monsoon is associated with centers of heavy rainfall anchored to the west coast of India, the Bay of Bengal, Indo-China and the South China Sea/Western Pacific region (Fig.2a). The low-level circulation is dominated by a large scale anticyclonic (clockwise in the Northern hemisphere) gyre circulation over the Indian Ocean. This anticyclone gives rise to a strong low level westerly flow across the Indian subcontinent and Indo-China, subsequently turning northward into East Asia and Japan. A dominant low level anticyclonic circulation, known as the West Pacific Subtropical High is located over the subtropical western Pacific, with prevailing easterlies in its southern flank, between the 10^{o} S-10^{o} N. The westerlies and easterlies converge over the South China Sea/ Philippines region, coinciding with the zone of heavy precipitation in this region. During El Niño, enhanced rainfall and low-level westerlies are found over the equatorial central Pacific (Fig. 2b). Reduced rainfall is found over the maritime continent and the subtropical western Pacific in both hemispheres. The rainfall pattern has been referred to as a "rainfall dipole", which is one of the many key signatures of El Niño. Note that the responses over the monsoon land regions are not very well defined, compared to its oceanic counterpart. In particular over the Indian subcontinent, the signal is mixed. Over the Indian Ocean anomalous easterlies are found between the equator and 15^{o} N, signaling a weakening of the Indian Ocean gyre circulation. The rainfall dipole, which is made up of general suppression in rainfall (sinking motion) over the monsoon region, and enhancement of rainfall (rising motion) in the equatorial central Pacific, is due to the eastward shift of the Walker circulation during El Niño.

<Fig. 2 near here>

During the austral summer, December-January-February (DJF), the zone of heavy rainfall shift south of the equator to maritime continent, northern Australia and the oceanic region further east (Fig.2c). The large scale circulation features low level easterlies over the northern hemisphere western Pacific and much of the Indian Ocean just north of the equator. Over the far western Pacific and the Indian Ocean, the flow turns southward and then eastward into the southern hemisphere, culminating in a belt of westerlies from the eastern Indian Ocean to 160° E. During an El Niño, rainfall anomaly occurs again in the form of a east-west dipole, with increased rainfall over the equatorial central Pacific and suppressed rainfall over the far western Pacific/maritime continent. In addition, a broad region of enhanced rainfall is found over the central and western India Ocean and an area of reduced rainfall over the eastern equatorial Indian Ocean. Together, these rainfall anomalies form a secondary dipole over the Indian Ocean. While Indian Ocean dipole appears as part of the signal of ENSO, it has also been suggested that the Indian Ocean dipole may also arises from regional coupled ocean-atmosphere processes that are independent of ENSO. Accompanying the anomalous rainfall are anomalous low level westerlies over the central Pacific, and easterlies over the far western Pacific and Indian Ocean, consistent with the eastward shift of the Walker circulation during El Niño.

In view of the above discussions, the relationship between rainfall over India and northern Australia, and El Niño / La Niña noted in Section 2 should only be considered as embedded in a major shift in the global rainfall and circulation patterns associated with ENSO. Note that composite pictures like those shown in Fig.2 only bring out common features for different El Niño /La Niña's, the actual rainfall anomalies may vary greatly regionally and for individual events.

4. Factors affecting monsoon-ENSO relationship

a. Regional Ocean-atmosphere processes

Recent studies have shown that in addition to the basin scale monsoon-ENSO mode associated with the shift of the Walker circulation, there are intrinsic modes of variability in the monsoon-ocean-atmosphere system, which may not bedirectly connected with ENSO, but may have strong impact of AAM variability. These modes stem from regional coupled ocean-atmosphere processes in the Indian Ocean, the western Pacific, South China Sea and Indonesian waters. The regional anomalies can amplify, oppose and/or modulate ENSO-induced direct changes as the AAM responds and adjusts to the ENSO forcings. The regional ocean-atmosphere processes regulate the SST and rainfall covariability in the monsoon region, through fluxes of heat and momentum at the ocean-atmosphere interface. This regional coupling covers a wide range of times scales ranging from the intraseasonal to interannual and beyond (see also discussion in Section 4d).

In a recent study, Lau and Wu (1999, 2000) identified three basic coupled monsoon-SST modes that underpin the dynamics of monsoon-ENSO relationships. Mode-1 is related to the well-know east-west shift of the Walker Circulation associated with ENSO, with anomalous low level easterlies over the western Pacific and the Indian subcontinent, coupled with reduced rainfall accompanying descending motion over the maritime continent and the eastern Indian Ocean (Fig. 3a). Mode-2 is mixed basin-scale and regional mode featuring a West Pacific Anticyclone (WPA) northeast of the Philippines over the East China Sea with reduced rainfall to the south and enhanced rainfall to the north of the WPA (Fig. 3b). A number of studies have suggested that the WPA has a strong influence on the climate of East Asia in both interannual and intraseasonal time scales (Lau et al 2000, Wang et al 2000). Mode-3 depicts a regional mode with a east-west rainfall dipole over the Indian Ocean and a WPA which is shifted northward over southern Japan compared to Mode-2 compared to Mode-2. The wind pattern suggests a possible inter-hemispheric connection between the southern hemisphere wintertime circulation and the Asian monsoon. This mode has a pronounced decadal scale variability (not shown) and may be related to the Indian Ocean dipole in SST reported by Webster et al (1999) and Saji et al (1999). More recent results show that the Indian Dipole mode is more pronounced during the austral summer monsoon. It is likely that the nature of monsoon-ENSO coupling is dependent on the interplay between the above intrinsic modes, in particular Mode 1 and 2. In order to account for the monsoon rainfall variability of a sub-region such as the Indian subcontinent, all three, or possibly the higher order modes, need to be considered

<insert Fig. 3 near here>

Using cumulative anomaly correlation (CAC), Lau and Wu (2000) has computed the year-by-year and mode-by-mode contribution to the potential predictability of the Asian summer monsoon based on "perfect knowledge" of the SST. For the South Asian monsoon (Fig. 4a), the Walker circulation effect (Mode-1) dominates. However, in order to achieve potential predictability higher than 0.5 (the 99% confidence level), the contributions from the regional modes (Mode-3 and higher order modes) are essential. As shown in Fig. 4a, the basin scale modes (Mode 1 and 2) including ENSO, have no impact on the South Asian monsoon rainfall in 1997, when the South Asia rainfall anomalies are accounted for by regional scale variability. In contrast, in 1998, the impact of the WPA (Mode-2) on the South Asian monsoon is very strong. For the East Asian monsoon (Fig. 4b), the WPA (Mode-2) has more impact than the Walker circulation (Mode-1). The dominant impact of the WPA in 1998 suggests that monsoon rainfall anomalies during that year would have been highly predictable provided that the WPA and associated SST (both regional and basin-scale) can be predicted.

<insert Fig. 4 near here>

b. Snow cover

A major factor that may confound the monsoon-ENSO relationship is the impact of snow cover on the evolution of the monsoon. In a report that dates back to the last century, Blanford (1884) first showed that the strength of the Indian summer monsoon may be affected by snow cover over the Himalayas. Subsequently, it was felt that the snow-monsoon relationship was not robust and snow cover had not been used to predict the Indian monsoon. Hahn and Shukla (1976) shows that Euraisan snow cover may also impact the Indian monsoon variability. There is now growing observational evidence suggesting that persistent winter snow cover over the Tibetan Plateau may delay or weaken the monsoon during the following summer. Increased snow cover increases the surface albedo reflecting more solar radiation from the land surface. Heat energy which would otherwise be used to heat up the land will be used to melt the extra snow. As a result, the land surface heats up slower during the spring and summer, reducing the land-sea contrast and therefore weakening the monsoon. Conversely, reduced snow in the previous winter may lead to enhanced monsoon rainfall. However, while Eurasian snow cover changes may be related to internal atmospheric processes, increased snow cover over Eurasian may not be independent of ENSO on interannual time scale.

Fig. 5 shows a composite relationship between monsoon-snow cover-ENSO. It can be seen that Eurasian snow cover is somewhat increased in the winter preceding a weak Indian monsoon, but the relationship is tenuous at best. Recently Yang (1996) and Sankar Rao et al (1996) showed that when the effect of ENSO is removed, the negative snow-monsoon correlation becomes more apparently. Using numerical experiments, Yang and Lau (1998) estimated the effect of ENSO on monsoon, by withholding the interaction between land surface processes (including snow), with the atmosphere and found that El Niño has a much stronger control on the monsoon than land surface processes. However, this result may be model dependent and has to be validated with experiment with different models, as well as more detailed data analysis. Clearly a better understanding of monsoon-ENSO relationship required the untangling of the monsoon-snow-ENSO relationship.

<insert Fig. 5 near here>

c. Land-atmosphere hydrologic feedback

Snow cover aside, land-atmosphere processes including vegetation interaction in general can affect monsoon and monsoon-ENSO relationship by altering the energy and water cycles within the monsoon regions, through surface heat fluxes and hydrologic feedback mechanisms, as illustrated in the schematics in Fig.6. For example, if the soil moisture content of the Asiatic land mass is abnormally high during the start of a monsoon season, land surface evaporation will be increased. This will lead to increased moistening of the atmospheric boundary layer, more unstable air masses and hence more convection and rainfall, resulting in a positive feedback leading to further moistening of the land region. However, the cloudy sky condition stemming from enhanced convection will shield off and reduce solar radiation from reaching the land surface, causing the land to cool. As the land mass cools off, the resulting decreased land-sea thermal contrast can only support a weaker large scale monsoon circulation, with reduced monsoon rainfall. This results in a negative feedback, halting further increase in soil moisture. These feedback mechanisms are dependent not only on local processes but also on the remote forcing such as forced large scale descent or ascent over the AAM region by ENSO. The large-scale vertical motions provide a strong control on atmospheric stability and initiation of convection. Even though the ENSO remote forcing has relatively slow time scales, its impact may be sufficient to tip the delicate balance of the aforementioned local feedback processes causing either the persistence of a given climate state or transition from one state to the other (Lau and Bua 1998).

<Fig. 6 near here>

d. Intraseasonal variability

One of the key characteristics of the monsoon is the presence of a rich spectrum of intraseasonal variability. These include quasi-periodic oscillations from 30-60 days, 10-20 days and transient waves of 3-5 days. The intraseasonal variabilities are generated by internal atmospheric dynamics but strongly modified by sea surface temperature and land surface processes (Ferranti et al 1999). They are responsible for the modulation of monsoon onsets, breaks and evolution regionally. Fig. 5 shows the two dominant extended EOF intraseasonal (20-70 days) variability of 850 hPa streamfunction variability over the Asian monsoon domain for May through September. The first mode shows a northward propagation of a dipole anomaly from the equatorial Indian Ocean to the Asian monsoon region on times scale of 10-20 days. The monsoon anomalies extend eastward along the equator to the eastern Pacific, reversing its sign in approximately 40 days. The eastward propagating component is associated with that of the Madden and Julian Oscillation (MJO). The northward propagation is a well-known feature of the Asian monsoon (Lau and Chan 1986, Krishnamurti and Subrahmanyam 1983). More interesting is the second mode, which depicts a stationary or slightly westward propagating streamfunction anomaly covering the subtropical western Pacific. This can be identified with the WPA feature in Mode-2 of the interannual variability (see discussion in Section 3a). The WPA appears to be amplified locally, following by signals moving in from the equatorial Indian Ocean region. Hence the WPA appears to be a common feature in both intraseasonal and interannual variability of the East Asian monsoon. The WPA also serves as an apparent center for a pan-Pacific teleconnection spanning the North Pacific and North America (not shown). Recent studies have also shown that there may be a common mode of intraseasonal and interannual variability associated with the Indian monsoon (Chen et al. 1999, Sperber et al 2000).

<insert Fig. 7 near here>

Intraseasonal variability, especially those in the lower frequency end of the spectrum, can have strong impacts on the seasonal mean monsoon climate. Over different regions, they can either strengthen or weaken the direct influence by ENSO on the monsoons. The similarity between the intraseasonal and interannual modes suggest that intraseasonal variability may lead to the excitation of interannual variability and vice versa. The monsoon-ENSO relationship can be confounded by strong intraseasonal oscillations. It has been suggested that, the near normal monsoon rainfall over India during the strong El Niño of 1997-98 may be due to the effects of pronounced intraseasonal variability, which brought copious rainfall to many parts of India, in spite of the tendency of ENSO to weaken the AAM.

e. Biennial variability

Rainfall records in many monsoon regions show a strong biennial tendency, i.e., a strong monsoon followed by a weak monsoon, and vice versa. Some aspects of this tendency can be discerned from Fig. 1. The origin of the biennial tendency in the monsoon is still unclear, but may be related to local air-sea interaction as well as basin scale coupled ocean-atmosphere processes (Meehl 1994, Shen and Lau 1995, Chang and Li 2000). Coincidentally strong biennial tendency has also been found in ENSO cycles. Except for the different time scale, the evolutionary features of the biennial oscillation in sea surface temperature, sea level pressure, wind and precipitation are very similar to that of ENSO (Rasmusson et al. 1990, Lau and Sheu 1988). Recent studies have suggested that strong monsoon-ENSO interactions may result in a strong biennial tendency in ENSO cycles in the form of a rapid development of an La Niña approximately 12 months after an El Niño or vice versa (Lau and Wu 2000).

<insert Fig.8 here>

Based on numerical experiments with an intermediate coupled ocean-atmosphere model, Kim and Lau (2000) showed that a key mechanism for the quasi-biennial tendency in ENSO evolution may be in the coupling of ENSO to monsoon wind forcing in the western Pacific. Figure 8 shows the time-longitude variation of model thermocline and surface wind anomalies in a control experiment without monsoon wind forcing (left panel) compared to those for an anomaly experiment in which interactive monsoon wind forcing is prescribed at a time lag of 6 month, with respect to the thermocline anomaly in the equatorial eastern Pacific. With monsoon wind forcing, the basic ENSO cycle features a basin wide stationary oscillation, with the wind and thermocline in quasi-equilibrium (left panel). The effect of the interactive monsoon surface wind forcing is to produce a more distinct eastward propagating signal in both wind and thermocline from the western Pacific (right panel). It is found that the time lag of 6 months, is crucial in governing the periodicity of the coupled monsoon-ENSO system, whereby a naturally occurring ENSO cycle (typically 3.5 – 4 years) can be entrained to a periodicity of approximately 24 months, depending on the strength of the monsoon wind coupling.

The following scenario seems to be operative in the coupled model. During the developing warm phase of El Niño in JJA, anomalous monsoon westerlies develop over the western equatorial Pacific and propagate eastward. The eastward propagating westerlies reinforce the deepening thermocline and rising SST in the central and eastern Pacific amplifying the El Niño signal there. However the monsoon westerlies also cause a shoaling of the thermocline in the western Pacific. This shoaling is communicated to the east Pacific via an eastward propagating upwelling Kelvin wave which initiates the turnaround of the SST and thermocline tendencies and eventually the reversal anomalies in the eastern Pacific. The process then repeats itself during the cold phase. In a basic ENSO cycle (without impact of monsoon), the SST and thermocline in the eastern

Pacific tends to peak in the boreal winter, the 6-month lags puts the maximum monsoon wind forcing in the summer following the peak warm phase. Hence the monsoon wind effect is exactly in quadrature with respect to the SST and thermocline anomalies, in a biennial oscillation. This above scenario is remarkable similar to that proposed by Shen and Lau (1995) of the tropospheric biennial oscillation based on monsoon rainfall and SST observations. To what extent, the aforementioned mechanism is operative in the real world remains to be validated by further data analysis and model experiments. Undoubtedly, the mechanism of the biennial variability is a key issue in unraveling the basic dynamics of monsoon-ENSO interactions.

f. Interdecadal variability

Because of the complexity and the multiple contributing factors, the relationship between monsoon and ENSO is likely to be non-stationary. Webster et al (1998) show that during the late 1800s and early 1900's the correlation between Indian rainfall and the Southern Oscillation Index (SOI) is relatively high (~ 0.6), but in the 1920-40, the correlation drops to less than 0.2 - 0.3. It rises to 0.5 - 0.6 again in the 1960-1980s. In the 1990-present decade, there is again a sharp decline in the correlation to less than 0.2. These changes appear to collaborate with changes in sea level pressure and large scale circulation patterns (Torrence and Webster 1999, Kumar et al 1999). Recently, Krishnamurthy and Goswamy (2000) find that there are distinct interdecadal and interannual signatures in the Walker circulation and the monsoon regional Hadley circulation, and that regional monsoon impacts depend on the interaction of these two basic time scales in a highly nonlinear manner. They find that during the warm phase of the interdecadal oscillation, El Niño events are more strongly related to the Indian monsoon, while La Niña events may not have significant relations. On the other hand, La Niña may have stronger impacts during the cold phase of the interdecadal SST oscillations. The results suggest that El Niño and La Niña impacts on the monsoon are not mirror images of each other and hence need to be consider separately. This inter-decadal variation in monsoon-ENSO relationship has also led to the speculation that the changes in monsoon-ENSO relationship may be related changes in the structure of ENSO, perhaps due to global warming (Kumar et al 1999). However these assertions should be treated with extreme caution, because of the uncertainty in the historical data records and the sensitivity of the analysis to long-term trends.

5. A new paradigm

Given the large number of factors that can affect monsoon variability and monsoon-ENSO relationships, it is clear that for better understanding of the predictability of the monsoon climate, a monsoon-centric view has to be adopted. Figure 9 encapsulates such a view of the monsoon climate system, at the center of which is the AAM. It is envisioned that that AAM is affected by a "fast" component, depicted in the lower left-hand corner of the schematic. This is the internal dynamic subsystem that includes moisture recycling and hydrologic feedback in the atmosphere. This fast system is dominated by synoptic (3-5 days), sub-synoptic to cloud scales (< 1 day) and can be identified with monsoon depressions, easterly waves, convective cloud clusters, and meso-scale complexes within the AAM region. Additionally, the monsoon climate is strongly affected by surface conditions in the adjacent oceans and land masses, represented as the "intermediate" subsystem in the lower right-land corner of Fig. 9. This subsystem possesses both fast and slow (weeks to months) time scales. The key elements in this subsystem consist of SST, wind, and surface humidity that determine heat and moisture fluxes over the oceans adjacent to the monsoon land mass. Also included as elements in the "intermediate" subsystem are soil moisture, vegetation, and snow cover that control the heat and moisture flux over the land regions of ASM.

Connecting the fast and intermediate subsystems is "intraseasonal variability" which comprises of the Madden and Julian Oscillations and other monsoonal low-frequency variability such as the biweekly oscillation, which have been linked to onset, breaks and revival of the ASM. Both the fast and intermediate subsystems are under the influence of remote forcings from planetary scale phenomena such as ENSO and other long-term secular variations of the global climate system from decadal variability to global warming. These remote forcings constitute the "slow" subsystem that is considered as external to the AAM, but yet can play an important role in altering the basic states of the monsoon atmosphere, the adjacent oceans, and land surfaces. These altered states may then lead to modulations of the probability distribution of monsoon states within the fast component. It is also plausible that the coupling of the fast and intermediate subsystems may influence the slow system. These two-way interactions are represented by the linkages labeled "teleconnections". As an example, SST anomalies in the Indian Ocean and the western Pacific are coupled to those in the eastern equatorial Pacific through east-west overturning in the equatorial atmosphere and oceans. Another example is the possible linkage between the equatorial SST to extratropical SST through large scale atmospheric circulation changes which are itself function of the equatorial SST (Lau and Nath 1996).

In the aforementioned paradigm, interannual predictability of the monsoon climate is determined by the strength of the linkages provided by the intermediate and the slow subsystems. The predictability of the monsoon climate evolves as the result of an inter-play between the relative influence of the fast, the intermediate, and the slow subsystems. The stronger control by the fast system, the less predictable is the ASM. The more influence by the slower subsystems, the more the ASM is predictable. In this view, the predictability of the monsoon evolves as a function of the slowly varying basic states and therefore will wax and wane over long time scales. Such a paradigm will to be helpful to put into the right context the question why is there an apparent weakening in the relationship between the Indian monsoon rainfall and the ENSO in the present decade?. It will at least point to the fact that there are various regional monsoon components that are subject to different sets of local and remote forcings, of which ENSO is only a part. Hence a weakening in relationship between one component of the monsoon system does not necessarily mean that the entire monsoon-ENSO relationship is undergoing such a change. Indeed there are indications that the relationship between ENSO and the East Asian/West Pacific monsoon system have remained robust in the recent decades (Wang et al. 2000).

6. Future prospects

Year after year, the occurrences of devastating monsoon related droughts and floods serve as a reminder that improved prediction of the monsoon rainfall is paramount for the well-being of millions living in the Asian Australian monsoon regions. Today, monsoon prediction is still a very challenging problem. Even armed with the knowledge of "perfect" lower boundary conditions provided by ENSO, a large part of the interannual monsoon rainfall variability may remain unpredictable. Hence progress in monsoon research will not be by leaps and bounds, and substantial improvement in monsoon prediction will not come, unless there is a systematic and organized research effort devoted to the better understanding and mining of monsoon predictability associated with ENSO, as well as other contributing factors discussed here.

Acknowledgement

This work is supported by the Global Modeling and Data Analysis Program of the Earth Science Enterprise, NASA, and the TRMM project. Thanks are due to Drs. S. Yang, K. M. Kim, and H. T. Wu for providing the figures and for discussions.

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Figure Captions

Figure 1 Time series of All-India rainfall anomaly, normalized by standard deviation, with respect to the base period 1871-1998. Dark shaded bars indicate years with peak El Niño warming in the equatorial eastern Pacific in following winter and light shaded bars, years with peak La Niña cooling in following winter.

Figure 2 Climatology of rainfall (with shading levels at 6, 9 12 mm/day) and 850 mb wind streamlines for a) JJA, c) DJF. Rainfall (with shading levels at 0.5, 2, 5 mm/day) and 850 mb streamline anomalies defined as warm events minus cold events for b) JJA and c) DJF.

Figure 3 Spatial distribution of dominant modes of 850 mb wind (streamfunction) and rainfall co-variability between Asian monsoon rainfall and global SST for a) Mode-1 , b) Mode-2 and 3) Mode-3. Rainfall units are in mm/day.

Figure 4 Histogram showing the mode-by- mode cumulative anomaly correlation as a function of years for a) the South Asia monsoon and b) the East Asia monsoon.

Figure 5 Composites of SOI-monsoon-snow relationship. The monsoon is defined using all-India summer rainfall. The snow cover is based on NOAA AVHRR data (adopted from Yang 1996).

Figure 6 Spatial distribution of 850 mb streamfunction of the first (left panel) and third (right panel) dominant modes of intraseasonal oscillation during the boreal summer.

Figure 7 Schematic showing elements of land-atmosphere water and energy cycles feedback for the AA-monsoon region. Negative feedback links are denoted by the symbol NF. The symbols are defined for precipitation (P), evaporation (E), soil moisture (S), cloudiness (CL), ground temperature (T_g), surface longwave radiation

(LW_{sfc}), surface short wave radiation (SW_{sfc}), sensible heat flux (SH). The sign of the anomalies indicate the possible feedback mechanisms for a persistent cool, wet monsoon climate when the ENSO forcing favoring upward motion over the AA-monsoon region.

Figure 8 Composites of simulated thermocline depth and regressed surface wind anomalies (shaded) averaged between 2° N and 2° S without monsoon wind forcing (left panel) and with interactive monsoon forcing, with 6 month lagging the peak thermocline anomalies (right panel). Contour interval for thermocline depth is 2 meters, and for surface wind is 0.2 m/s.

Figure 9 Schematic showing a unifying framework for study monsoon variablity and predictability and their relationships with different component of the earth's climate subsystems.

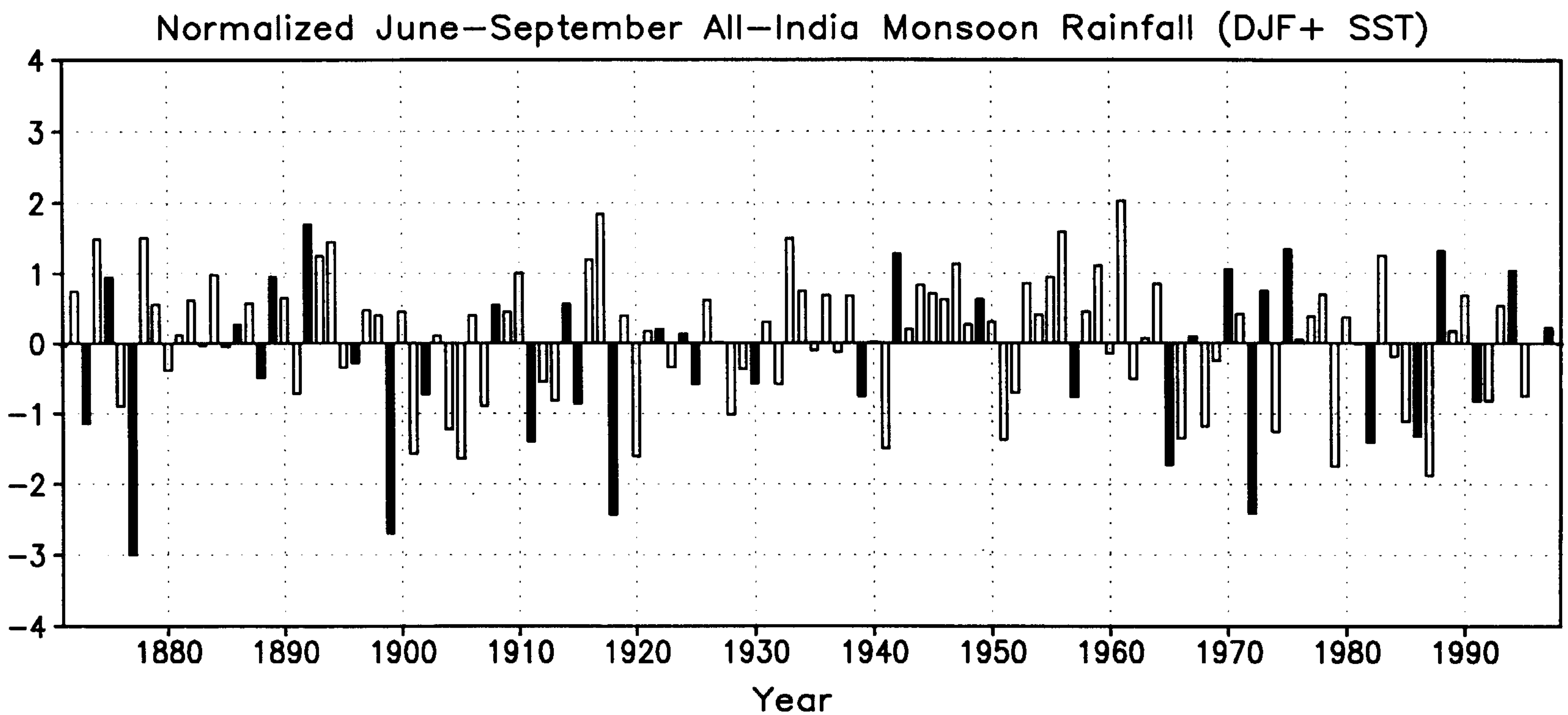

Normalized June–September All–India Monsoon Rainfall (DJF+ SST)
4
3
2
1
0
–1
–2
–3
–4
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

Fig. 1

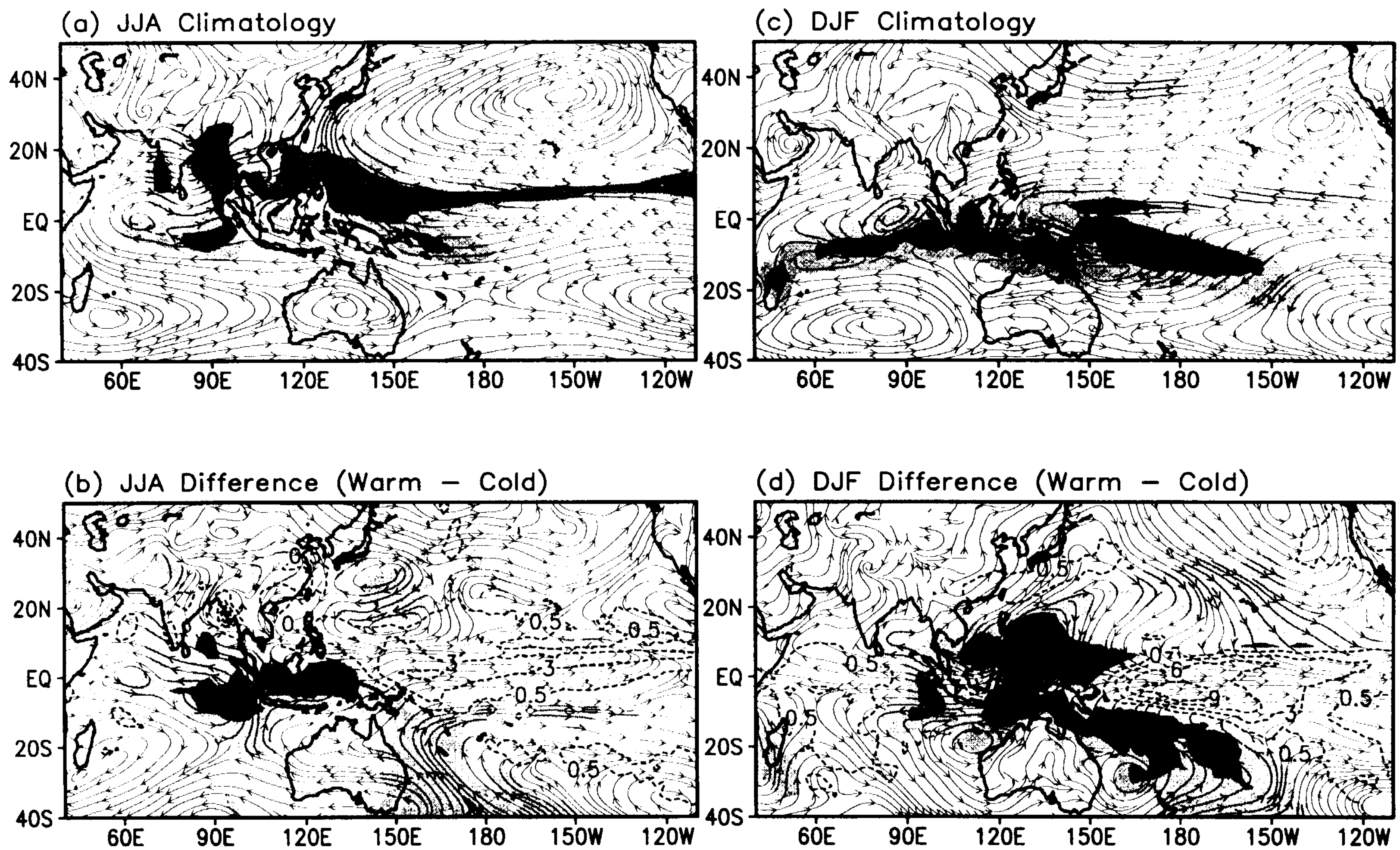

(a) JJA Climatology
(c) DJF Climatology
(b) JJA Difference (Warm – Cold)
(d) DJF Difference (Warm – Cold)
40N
20N
EQ
20S
40S
60E
90E
120E
150E
180
150W
120W
0.5
3
6
9

Fig. 2

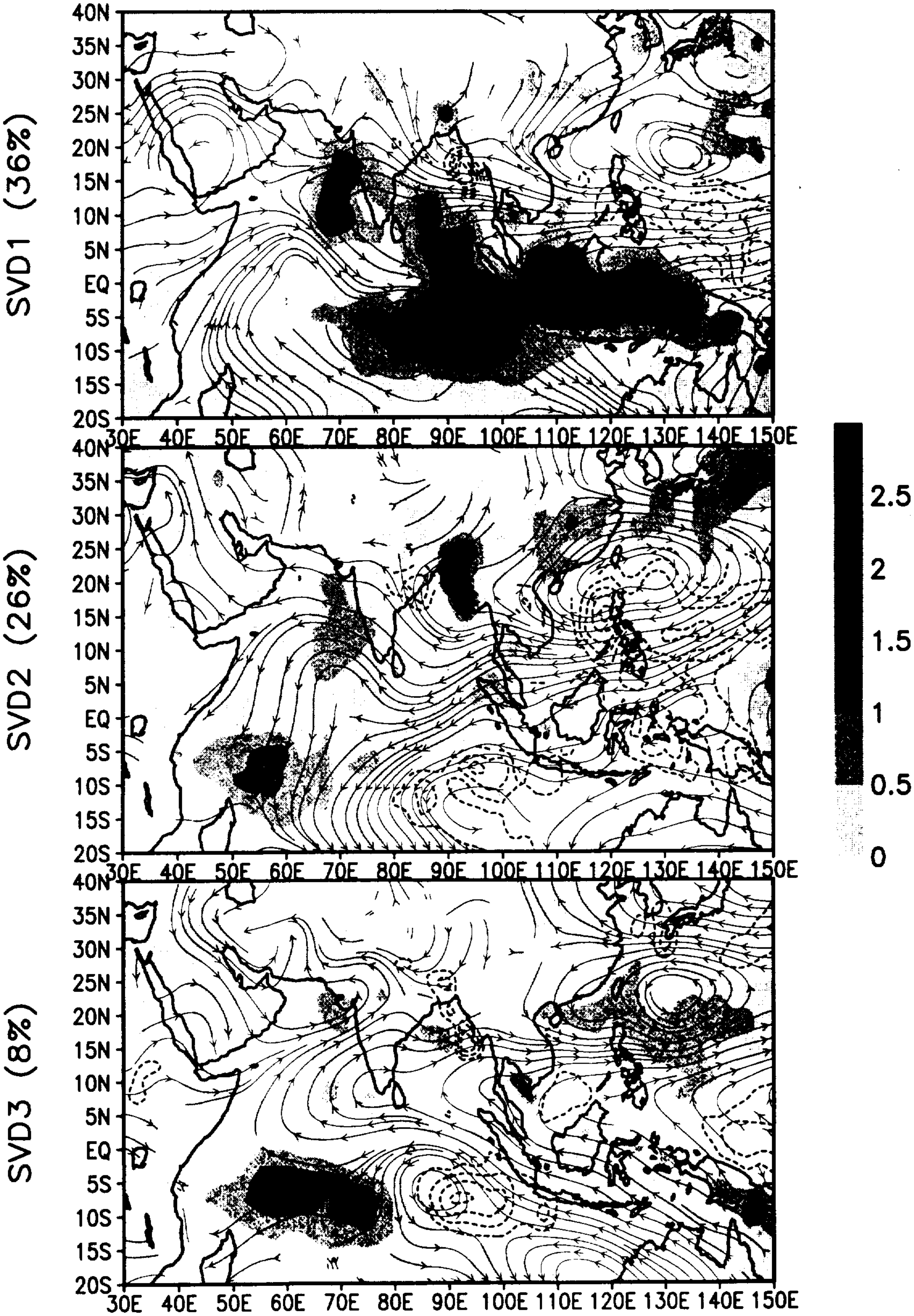
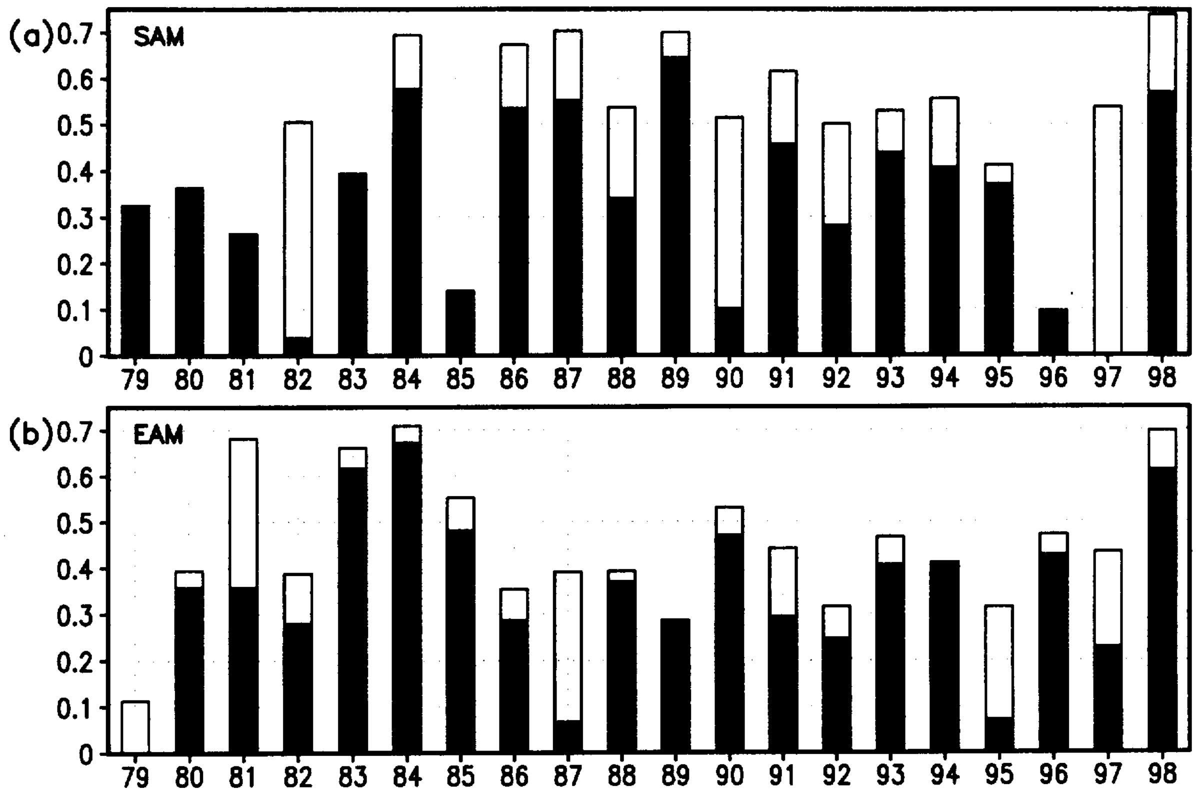

SVD1 (36%)
SVD2 (26%)
SVD3 (8%)
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
150E
2.5
2
1.5
1
0.5
0

Fig. 3



(a)
SAM
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98
(b)
EAM
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98

Fig 4

SIRM850/20-/0f/May-Aug

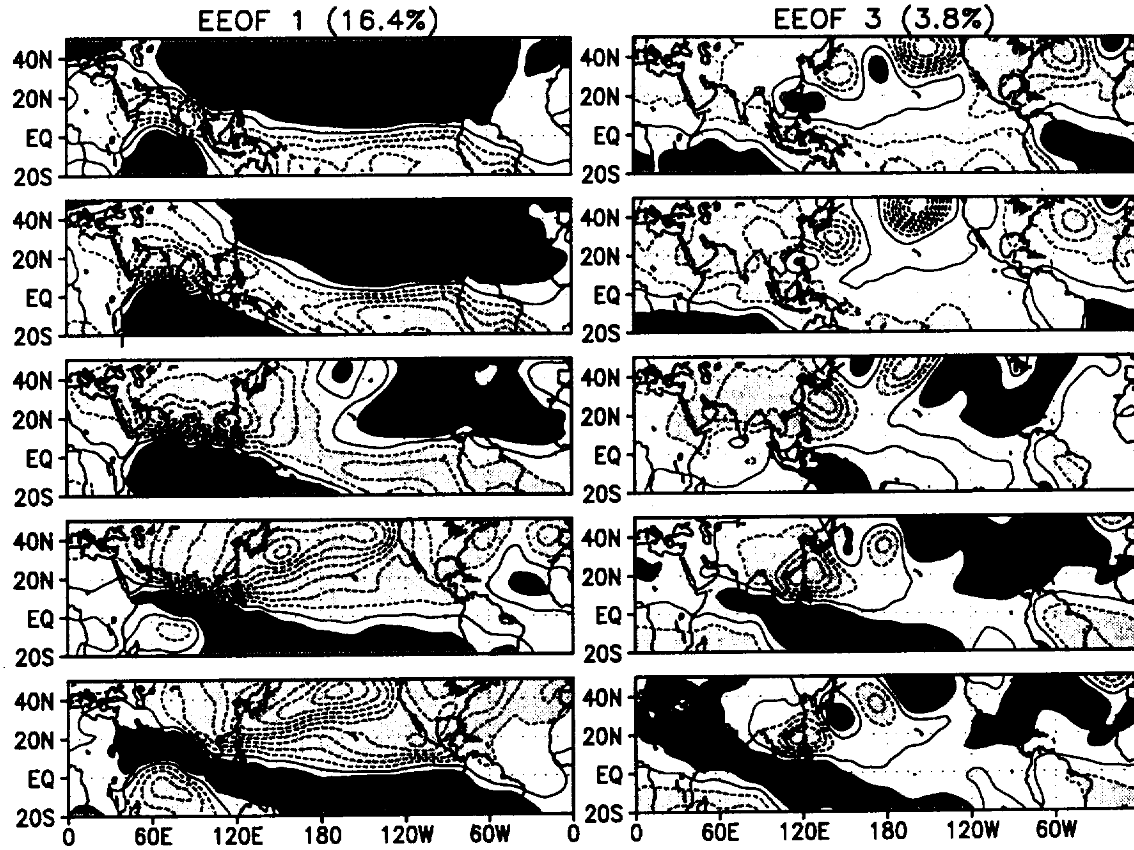


Fig. 5

SOI-Monsoon-Snow for El Nino Years

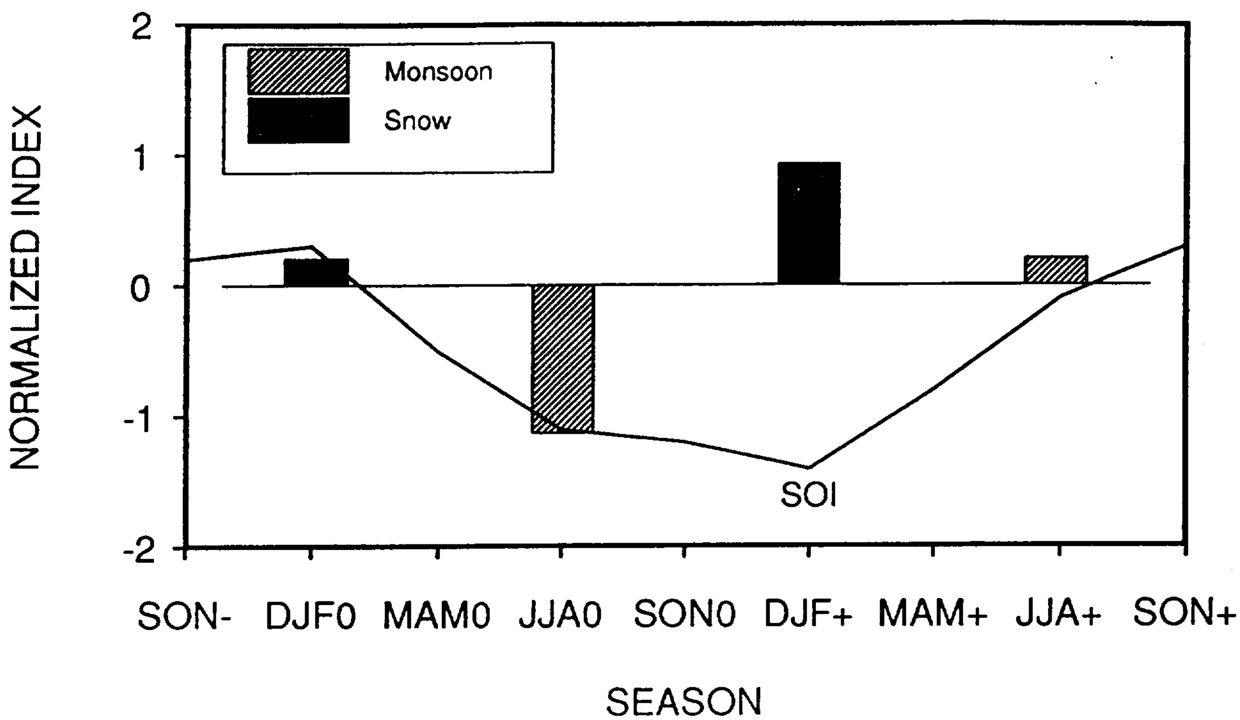


Fig. 6

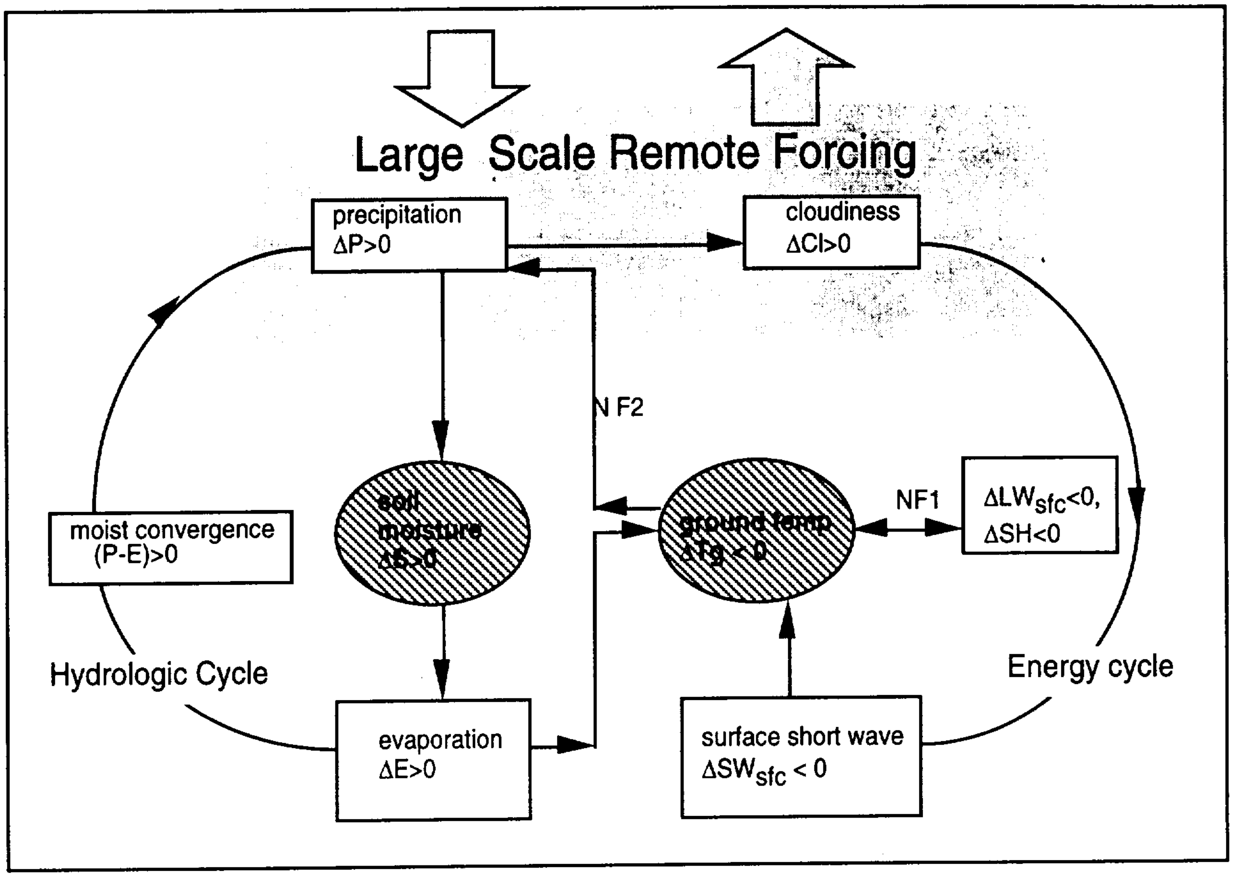
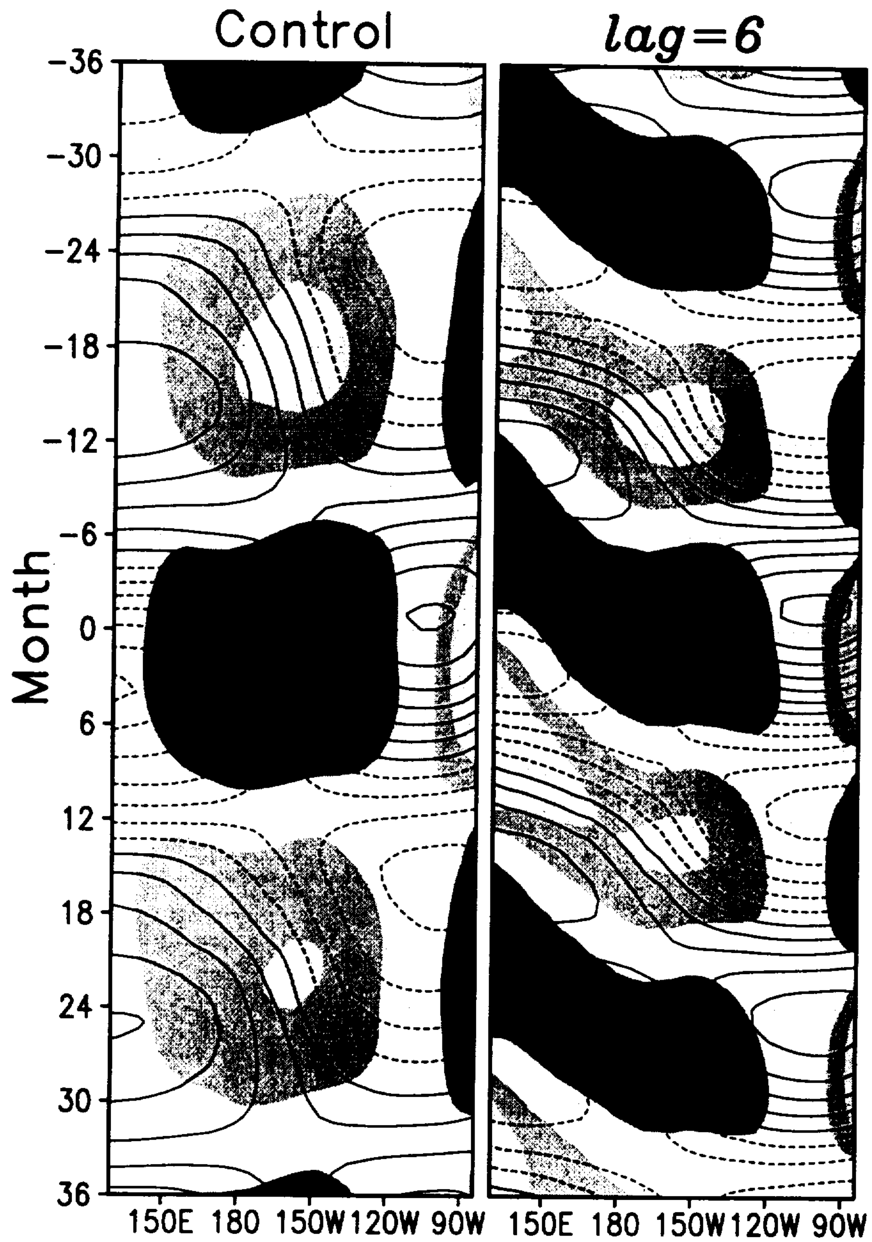

Large Scale Remote Forcing
precipitation $\Delta P>0$
cloudiness $\Delta Cl>0$
N F2
moist convergence (P-E)>0
soil moisture $\Delta S>0$
ground temp $\Delta Tg < 0$
NF1
$\Delta LW_{sfc}<0$, $\Delta SH<0$
Hydrologic Cycle
Energy cycle
evaporation $\Delta E>0$
surface short wave $\Delta SW_{sfc} < 0$

Figure 7



Control
lag=6
Month
-36
-30
-24
-18
-12
-6
0
6
12
18
24
30
36
150E 180 150W 120W 90W
150E 180 150W 120W 90W

Fig. 8

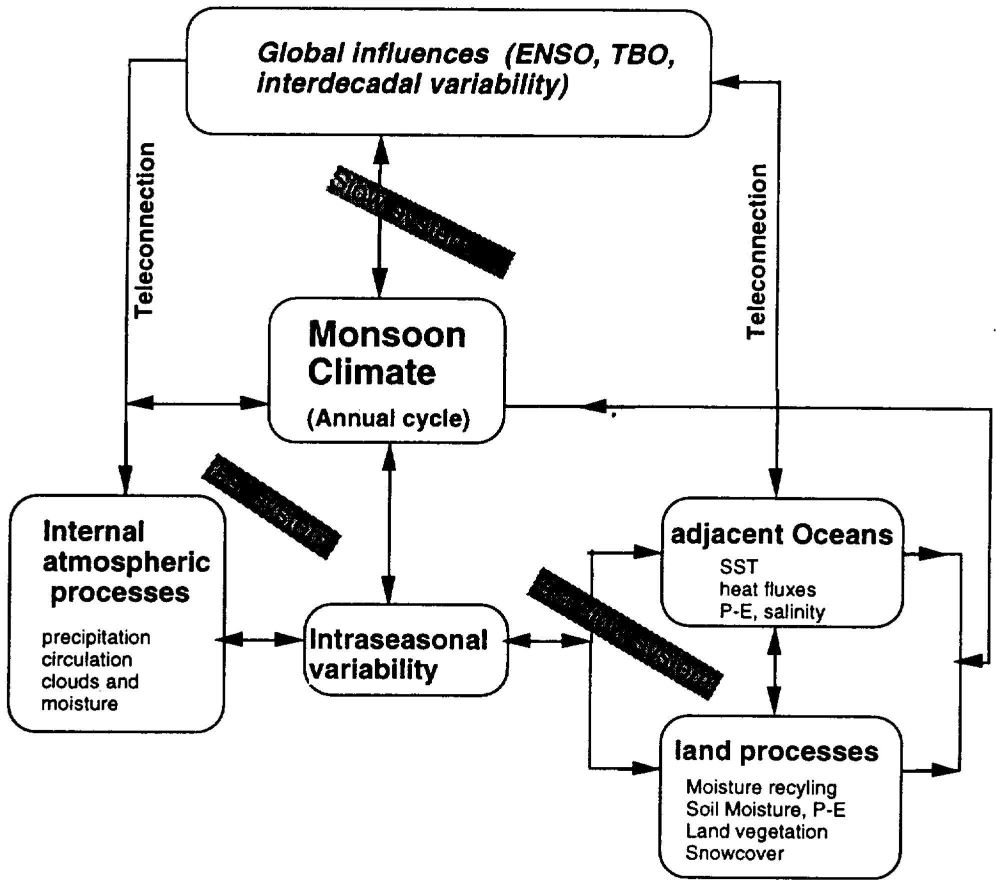

Global influences (ENSO, TBO, interdecadal variability)
Teleconnection
Teleconnection
Monsoon Climate
(Annual cycle)
Internal atmospheric processes
precipitation
circulation
clouds and
moisture
Intraseasonal variability
adjacent Oceans
SST
heat fluxes
P-E, salinity
land processes
Moisture recyling
Soil Moisture, P-E
Land vegetation
Snowcover

Fig. 9