The Annual Cycle, Intraseasonal Oscillations, and Roadblock to Seasonal Predictability of the Asian Summer Monsoon

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ABSTRACT

Factors responsible for limited predictability of the Asian summer monsoon (ASM) are investigated within a conceptual framework for predictability. Predictability of the seasonal mean depends on the interannual variability (IAV) of the monsoon annual cycle (MAC) and is determined by relative contribution of the predictable "external" component of IAV compared to the unpredictable "internal" IAV. Contributions of slow processes such as those involving air–sea interactions associated with the El Niño–Southern Oscillation (ENSO) or local warm ocean–atmosphere interactions in generating IAV of the MAC are reviewed. Empirical evidence that these air–sea interactions modulate the MAC is presented. Estimates of internal IAV have been made from observations as well as atmospheric model simulations. In contrast to a large part of the Tropics where the summer climate is predictable, with the internal variability being much smaller than the external one, the limited predictability of the Asian monsoon appears to be due to the fact that the contribution from the external IAV over the region is relatively weak and comparable to that from internal IAV.

Cause for large internal IAV over the ASM region is investigated, and it is proposed that the internal IAV of the MAC is primarily due to interaction between the MAC and the summer intraseasonal oscillations (ISOs). Two mechanisms through which ISOs lead to internal IAV of the MAC are unraveled. The seasonal bias of the ISO anomalies can influence the seasonal mean if the spatial structure of the ISO has significant projection on that of the seasonal mean and if frequency of occurrence of positive and negative phases is unequal. Evidence supporting this is presented. In addition, it is demonstrated that the chaotic summer ISOs modulated by the annually varying forcing associated with the "slow annual cycle" can lead to IAV of the seasonal mean. Empirical evidence that IAV of ISO activity is related to IAV of the seasonal mean or MAC is also presented.

Thus, the Asian monsoon would remain a difficult system to predict. To exploit the predictable signal, however, it is imperative that systematic bias of the models is improved and the space–time structure of the summer ISOs is simulated accurately.

1. Introduction

A strong annual cycle with rainy summer and dry winter seasons is a characteristic feature of the Asian monsoon. As the agrarian economy and the drinking water requirements of the region depend critically on the monsoon rains, agricultural practices and social events of the people in the region are strongly tied up with the annual cycle (Zimmermann 1987). Even as the green revolution steadily increased food productivity over the last four decades, a modest decrease in the monsoon rainfall (e.g., 10% of long-term mean) leads to a significant decrease in rice production over India (Abrol and Gadgil 1999; Gadgil 1995; Parthasarathy et

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al. 1988; Swaminathan 1987; Webster et al. 1998). The interannual variability (IAV) of the monsoon rainfall may have even larger impact on agricultural productivity in the coming years, as the growth rates of agricultural production have decreased in recent years in association with the fatigue of the green revolution (Gadgil et al. 1999). Extremes in monsoon rainfall lead to devastating floods and droughts (Mooley and Shukla 1987; Shukla 1987; Sikka 1999; Webster et al. 1998), causing enormous economic loss and human misery. The rainfall within the monsoon season, however, does not occur as a continuous deluge but is punctuated by monsoon intraseasonal oscillations (ISOs) that manifest in prolonged spells of dry and wet conditions sometimes lasting for 2–3 weeks. Extended above-normal rain spells represent periods when the monsoon has been vigorous or "active" while the dry spells represent periods when the monsoon takes a "break" (Ramamurthy 1969) from its activity and hence are known as active and break conditions, respectively (Gadgil 2003; Goswami 2005; Webster et al. 1998). Frequency of occurrence of active and break spells within the season influences the seasonal mean and hence agricultural production. Knowledge of the active and break spells is important for sowing, harvesting of crops, and water management within the season. Furthermore, long breaks in critical growth periods also lead to a substantially reduced yield of certain crops (Gadgil and Rao 2000). Therefore, "long-range" forecasting of seasonal mean monsoon at least one season in advance and "extended range" forecasting of dry and wet spells of the subseasonal variability 2–3 weeks in advance are of great importance.

For over a century, attempts to predict seasonal mean monsoon rainfall have been made using empirical methods (Blanford 1884; Goswami and Srividya 1996; Gowarikar et al. 1989; Iyengar and Kanth 2004; Sahai et al. 2003; Walker 1923, 1924). The empirical methods have been useful in providing guidance for seasonal forecasting and have reasonable skill when the monsoon is close to normal but have little skill in predicting the extreme events. All empirical models failed to predict the severe drought of the 2002 Indian monsoon. Dynamical prediction of the seasonal mean using a state-of-the-art climate model, therefore, offers a logical alternative to empirical prediction of the monsoon. Over the last couple of decades, the climate models have improved steadily in simulating the mean global climate (Gates et al. 1999), and a conceptual framework for predicting the tropical climate has also been established (Charney and Shukla 1981; Shukla 1981, 1998). Following the seminal work of Charney and Shukla (1981), a series of sensitivity studies with climate models (Anderson et al. 1999; Fennessy and Shukla 1994; Kumar and Hoerling 1995; Lau 1985; Shukla and Wallace 1983) has established that the interannual variability of the tropical climate is largely driven by slowly varying anomalous boundary conditions (ABCs) and is much less sensitive to initial conditions and hence more predictable compared to the extratropical climate. While this conclusion is generally true over a large part of the Tropics, it has also come to light over the last decade that the summer climate over the Asian monsoon region appears to be an exception within the Tropics, simulation of which is quite sensitive to initial conditions (Brankovic and Palmer 2000; Cherchi and Navarra 2003; Krishnamurthy and Shukla 2000; Sperber and Palmer 1996; Sperber et al. 2001). The current skill of most atmospheric GCMs with perfect boundary conditions in predicting Asian summer monsoon (ASM) precipitation is, however, insignificant (e.g., Kang et al. (2004); Wang et al. (2004)). Sensitivity of simulation of the seasonal mean to initial conditions indicates that the interannual variability of the seasonal mean is governed partly by "internal" low-frequency (LF) variability in addition to contribution from the ABCs.

The first Climate Variability and Predictability (CLIVAR) decade has witnessed major advances in understanding several aspects of ASM-related climate variability. For example, it is recognized that the El Niño–Southern Oscillation (ENSO) and ASM are not independent entities but are components of a coupled ocean–atmosphere oscillation (Loschnigg et al. 2003; Wu and Kirtman 2004). Better understanding of the dynamical origin and northward propagation of the summer ISOs has evolved (Chatterjee and Goswami 2004; Jiang et al. 2004; Wang and Xie 1997) and air–sea interactions associated with the summer ISOs have been unraveled (Fu et al. 2003; Sengupta et al. 2001; Waliser et al. 2004). Furthermore, it has been demonstrated that extended-range prediction of phases of the summer ISOs up to three weeks in advance is feasible (Goswami and Xavier 2003; Webster and Hoyos 2004). In light of these major achievements, the failure in predicting the mean south Asian (SA) summer monsoon has remained the single major enigma. Why is dynamical prediction of seasonal Asian monsoon so difficult, when the skill of dynamical prediction of seasonal climate over a large part of the Tropics has steadily improved over the last decade and shows good promise for the future? Is it because the simulation of the mean Asian summer monsoon by GCMs is still too poor and the systematic biases are still too large? Or, is there a more fundamental reason for the poor predictability of the Asian monsoon?

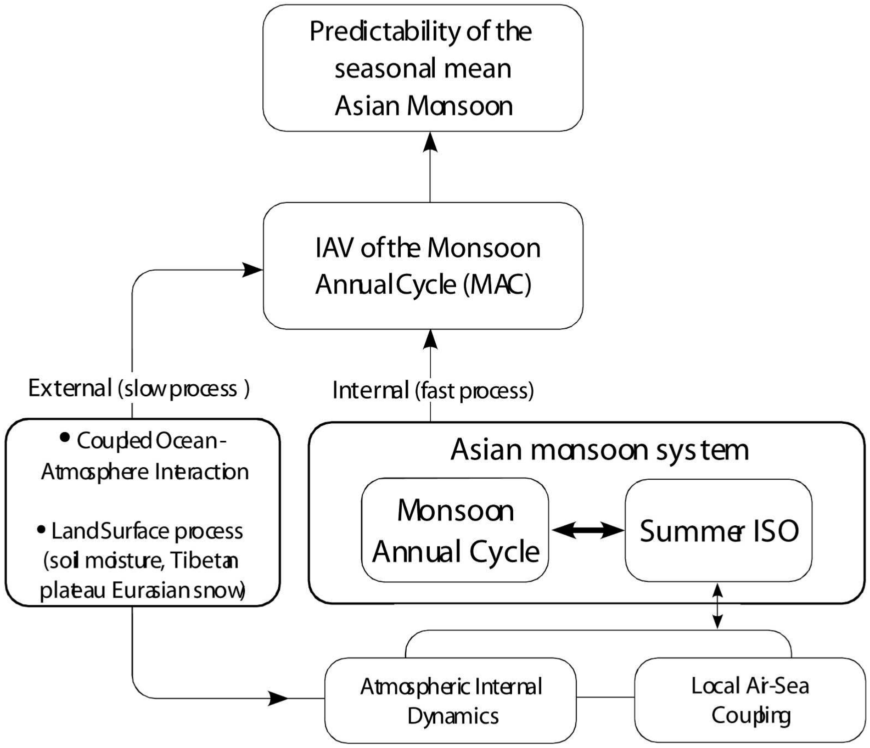

FIG. 1. A schematic picture of factors contributing to the predictability of the seasonal mean Asian monsoon.

Here, we present a broad framework for understanding the factors limiting the predictability of the seasonal mean monsoon (Fig. 1) and indicate that there is indeed a fundamental reason for the poor predictability of the Asian summer monsoon. At the heart of the problem is the monsoon annual cycle (MAC) mutually interacting with the monsoon ISOs. Predictability of the seasonal mean monsoon depends on the IAV of the MAC. The MAC, on the other hand, could be modulated by two classes of processes. The slowly varying ABC we referred to earlier in the context of an AGCM is nothing but a manifestation of slow unstable oscillations of the coupled ocean–atmosphere system such as the ENSO. As the spatial scale of these coupled oscillations is large compared to the spatial scale of the Asian monsoon system and the temporal scale is much larger than a year, they essentially modulate the MAC. Other feedbacks within the ocean–atmosphere system such as soil moisture–radiation feedback (Meehl 1987), Tibetan Plateau (TP) heating or Eurasian snow cover feedback, etc., that have time scales longer than a year also lead to a slow modulation of the MAC. We refer to these modification of the MAC associated with the slow processes as "external." The other process that could also lead to IAV of the MAC is through nonlinear interaction with the summer monsoon ISOs. Since ISOs themselves arise from internal atmospheric dynamics involving feedback between convection and dynamics, the component of IAV of the MAC governed by ISOs is sensitive to initial conditions. This component of IAV of the MAC is termed as of internal origin, as it arises through fast processes. The predictability of the seasonal mean monsoon, therefore, depends on the relative contribution of the predictable external component and unpredictable internal component to the IAV of the MAC. The seasonal mean monsoon would have high predictability over regions of the Tropics where the contribution of the external component to IAV of the MAC is much larger than that from the internal component. On the other hand, regions of the Tropics where the contribution of the external component to IAV of the MAC is comparable to that from the internal component would have poor predictability of the seasonal mean. Two fundamental aspects of the problem are the description of the Asian monsoon as a seasonal cycle and the role of the summer monsoon ISOs. The important features of MAC are highlighted in section 2. Evidence of IAV of the MAC is shown in section 3, and its association with slowly varying ABC is indicated. How ocean–atmosphere coupling could lead to interannual variability of the MAC is indicated in this section. The role of the Tibetan Plateau heating on the

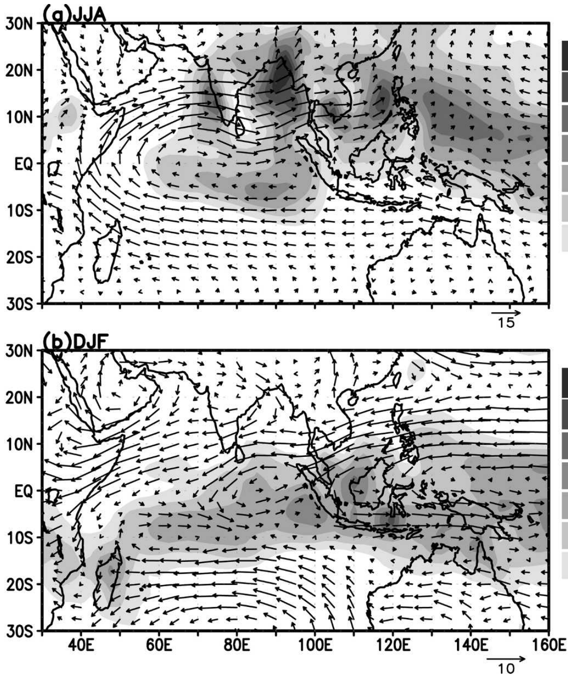

FIG. 2. Seasonal cycle of precipitation (mm day^{-1}) and low-level winds (m s^{-1}) over the Asian monsoon region. (a) Climatological mean JJA precipitation from CMAP and 850-hPa winds from NCEP–NCAR reanalysis. (b) Same as in (a), but for DJF. Scale for wind vectors is shown at the bottom of each panel. Precipitation more than 4 mm day^{-1} is shaded.

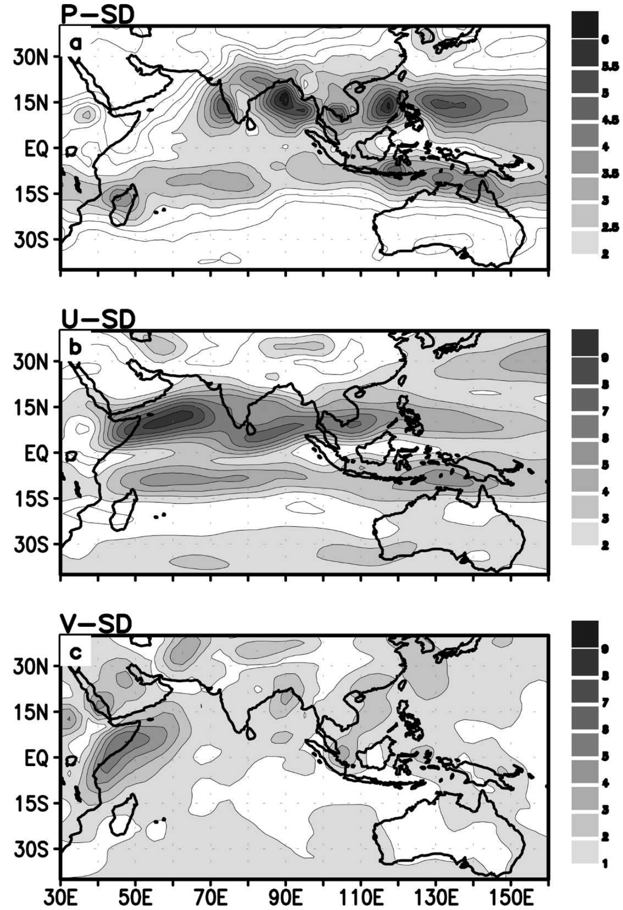

FIG. 3. Amplitude of climatological mean AC as defined by the std dev of climatological monthly means of (a) precipitation (mm day^{-1}), (b) zonal wind at 850 hPa (m s^{-1}), and (c) meridional wind at 850 hPa (m s^{-1}).

MAC is indicated in section 4. Scale interaction through which ISOs influence the MAC is described in section 5, and evidence of how the summer ISOs influence the MAC is presented from observations. Estimates of contribution from internal variability to IAV of the monsoon and that of predictability are presented in section 6. Main conclusions are summarized in section 7.

2. The monsoon annual cycle

The annual cycle is embodied in the very definition of the monsoon, namely, seasonal reversal of winds and precipitation (Ramage 1971) and has been discussed extensively (Hastenrath 1996; Ramage 1971; Webster et al. 1998). Usually, the Asian summer monsoon begins in May and ends in September while the Australian summer monsoon begins in December and ends in March. Here, we shall concentrate primarily on the annual cycle of precipitation and low-level winds over the Asian–Australian monsoon region as shown in Fig. 2. The amplitude of the climatological mean annual cycle (AC) of precipitation and that of the zonal and meridional winds at 850 hPa are shown in Fig. 3. The largest amplitude of the AC of precipitation occurs over the Asian and the Australian monsoon regions. The largest amplitude of the AC for zonal winds at low level occur over the low-level westerly jet (LLJ) region of the central and western Arabian Sea while that for the meridional winds occur over the western equatorial Indian Ocean (IO) and Somalia.

The AC of the monsoon is a manifestation of the seasonal migration of the zonally oriented belt of precipitation or the intertropical convergence zone (ITCZ; Gadgil 2003). Meridional migration of the ITCZ over the Indian monsoon region (70°–90°E) and over the East Asian (EA) monsoon region (120°–140°E) is shown in Figs. 4a,b using precipitation data from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996). A characteristic feature of the AC of the Indian monsoon is the onset associated with rapid transition of the high precipitation zone from near the equator to about 15°N

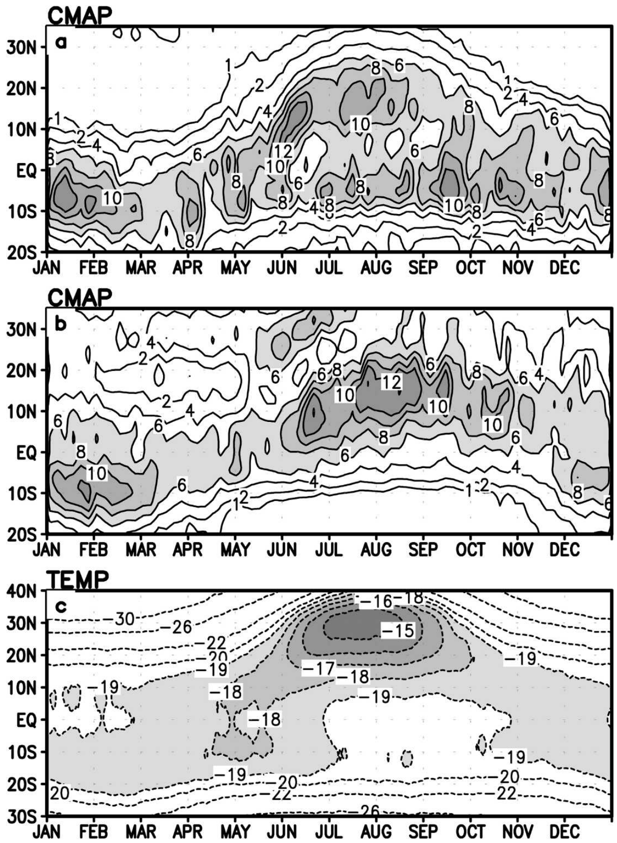

FIG. 4. Annual evolution of the ITCZ over, (a) the Indian monsoon region, defined by climatological precipitation (mm day^{-1}) averaged between 70° and 90°E and (b) the Australian monsoon region, defined by climatological precipitation (mm day^{-1}) averaged between 120° and 140°E. (c) Annual evolution of climatological mean temperature averaged between 200 and 600 hPa and averaged over the Asian monsoon region between 30° and 110°E in °C.

toward the end of May and beginning of June. Other characteristics are the primary ITCZ over the continental region between 20° and 25°N, the secondary ITCZ between the equator and 10°S, and withdrawal in late September (Fig. 4a). During the Australian summer monsoon (December–March), the ITCZ is active between the equator and 15°S with dry conditions in the Northern Hemisphere. The onset of the East Asian summer monsoon (EAM) takes place in several stages (Wu and Wang 2001). The ITCZ is weak during April and the first onset of the EAM takes place in mid-May with rapid transition and setting up of the meiyu front. The second onset of the EAM takes place in early June with the southern ITCZ moving rapidly to about 20°N and setting up dry condition south of the equator (Fig. 4b). The seasonal migration of the ITCZ is a result of seasonal evolution of the meridional gradient of tropospheric heating illustrated by the evolution of the mean temperature of the tropospheric layer between 200 and 600 hPa averaged between 30° and 100°E (Fig. 4c). The meridional temperature gradient reverses sign around the time of onset of the south Asian summer monsoon. It may be noted that after the onset, the tropospheric temperature in the north may be affected by the convective heating associated with the ITCZ. The reversal of meridional temperature gradient ushering the onset of the monsoon is, however, not affected by the ITCZ heating. The heating over the Tibetan Plateau plays a crucial role in this seasonal evolution of the meridional gradient of heating (Wu and Zhang 1998; Wu et al. 2002; Yanai et al. 1992) and is an important driving mechanism for the MAC.

Summer ISOs and MAC

The monsoon ISOs also play an important role in determining the climatological MAC (Figs. 3 and 4). It may be noted from Fig. 4a that the climatological mean daily precipitation, based on data for more than 25 yr, still contains some residual intraseasonal variability and "singularity" such as the rapid northward movement of the rain belt by 10°–15° within a short time during the onset phase and fluctuations within the season with a period of about a month. The residual ISO and singularity in the climatological MAC is due to phase locking of monsoon ISOs with a certain phase of the annual cycle (Kang et al. 1989; Wang and Xu 1997). Wang and Xu (1997) and Kang et al. (1999) call them "climatological intraseasonal oscillations" (CISOs). Thus, the MAC contains a "slow annual cycle" primarily due to the external forcing and a "fast annual cycle" arising from the ISOs (Wang and LinHo 2002). We separate the slow annual cycle component from the climatological pentad mean CMAP (Xie and Arkin (1996)) using a harmonic analysis and by constructing a sum of the annual mean and the first three harmonics. The difference between the climatological mean annual cycle and the slow annual cycle represents the fast annual cycle. The amplitudes of the slow and the fast components of the MAC of precipitation are shown in Figs. 5a,b. The ratio between the two (Fig. 5c) shows that the fast annual cycle contributes between 20% and 40% over most of the Asian–Australian monsoon region. There are regions such as the western Indian Ocean and Arabia, south equatorial eastern Indian Ocean, and equatorial western Pacific, where the contribution of the fast annual cycle could be even larger than that of the slow annual cycle. The contribution to the seasonal evolution of the MAC (Figs. 3a,b) from the slow and fast annual cycles is shown in Fig. 6. The south-to-north transition of the rain belt associated with the slow annual cycle smoothly follows the evolution of the solar

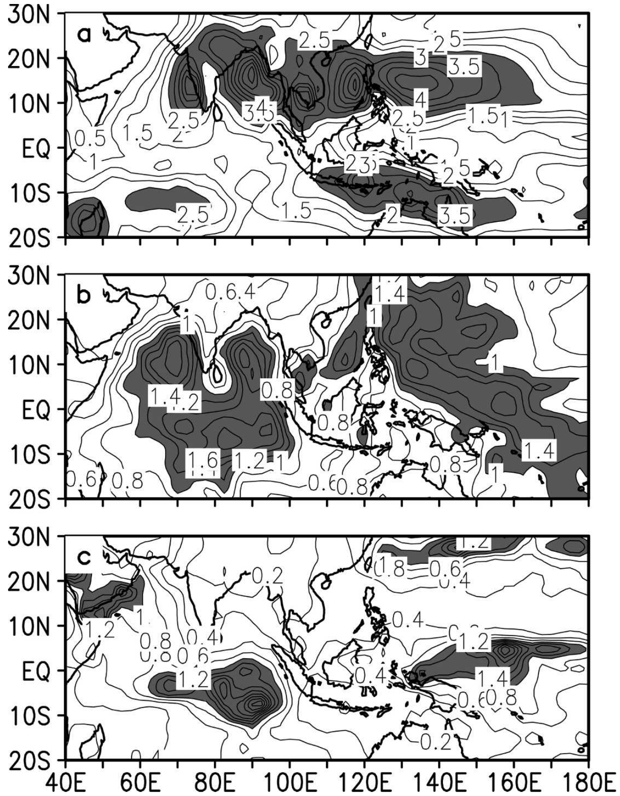

FIG. 5. Amplitude of the climatological mean (a) slow annual cycle, (b) fast annual cycle of precipitation (mm day^{-1}), and (c) ratio between the slow and fast annual cycles.

heating over the SA monsoon region (Fig. 6a) but lags behind it in the EA monsoon region (Fig. 6b) due to thermal inertia of the larger ocean involved in the later region. Over the SA monsoon region, the main contribution of the fast annual cycle comes during the onset (June) and withdrawal (September) in the form of northward-propagating ISO events (Fig. 6c). Even over the EA monsoon region, a large contribution of the fast annual cycle is seen at the time of onset in the form of a northward-propagating ISO event (Fig. 6d). Thus, the summer ISOs are closely tied up with the MAC and represent an important and integral component of the Asian–Australian monsoon system.

3. IAV of the MAC: Ocean–atmosphere coupling

One example of the way in which ocean–atmosphere interaction introduces IAV of the MAC is through the mutual interaction between the ENSO and the monsoon. This interaction is primarily through the change in the equatorial Walker circulation influencing the regional Hadley circulation associated with the Asian monsoon (Goswami 1998; Lau and Nath 2000; Webster et al. 1998). Since the pioneering work of Sir Gilbert Walker (Walker 1924), the influence of the ENSO on the ASM has been noted (Rasmusson and Carpenter 1983; Shukla 1987; Sikka 1980). As the strong heat source associated with the ASM could influence the atmospheric circulation in a significant way, it has also been recognized that it could modify the surface stresses over the central and western Pacific and influence the strength and evolution of the ENSO (Chung and Nigam 1999; Kirtman and Shukla 2000; Yasunari 1990). These independent studies of ENSO influence on the ASM and ASM influence on the ENSO indicate that the ENSO and the ASM are not independent phenomena but part of a coupled ocean–atmosphere oscillation. Led by this recognition several recent studies with coupled ocean–atmosphere GCMs (Loschnigg et al. 2003; Wu and Kirtman 2004; Yu et al. 2003) investigate IAV of the ASM due to air–sea interaction involving ASM and the ENSO. These studies indicate that the observed biennial tendency of the ASM may be a result of such air–sea coupling. Based on analysis of simulations of their coupled model, Wu and Kirtman (2004) propose a plausible mechanism through which a tropical biennial oscillation (TBO) may be generated. A strong ASM during June–August (JJA) can enhance surface easterlies in the central equatorial Pacific, induce an eastward-propagating upwelling Kelvin wave, and give rise to negative SST anomalies in the eastern Pacific that amplify through air–sea interactions. Colder SST in the eastern Pacific is also associated with warmer SST in the western Pacific. A strong ASM also cools the Indian Ocean through enhanced evaporation and upwelling. Associated intensification of the Walker circulation leads to divergence of moisture supply in the western Indian Ocean. Reduced moisture supply at low levels together with upper-level subsidence leads to a weaker ASM during the next summer. A weak ASM induces opposite affects and can lead to a stronger monsoon next year. This indicates that ocean–atmosphere interaction could generate IAV of the ASM via generation of TBO signal.

This two-way interaction between the monsoon and ENSO led to floating of the "monsoon year" concept of climate year in the Tropics. However, the recent analysis of Ailikun and Yasunari (2001) indicates that the biennial transition takes place within the summer monsoon season. They found that the variability of the Asian monsoon in the early summer (June) is associated with the anomalous state of the ENSO in the previous winter while that of the mid–late summer (July–September) is associated with the anomalous state of the ENSO in the following winter. Their finding that the all-India monsoon rainfall in September is well cor-

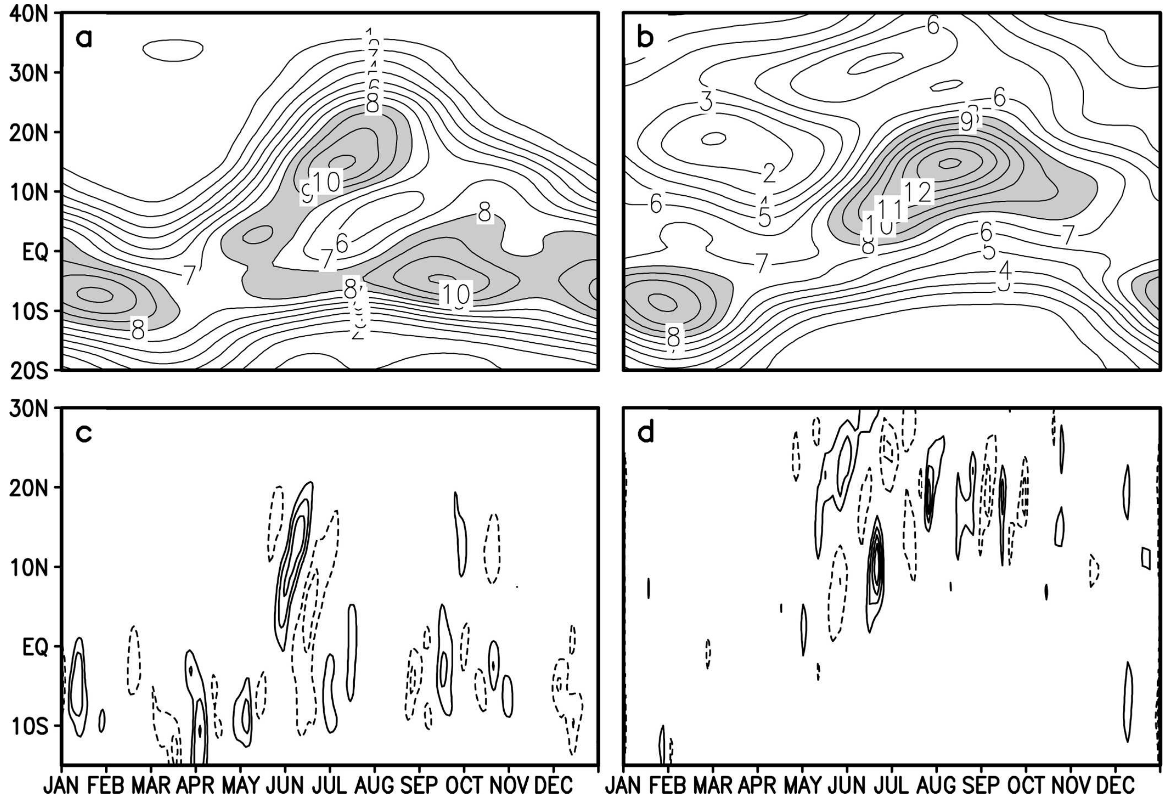

FIG. 6. Contribution of the slow annual cycle to the seasonal evolution of ITCZ (precipitation; mm day^{-1}) over (a) the Indian region (70°–90°E) and (b) the Australian monsoon region (120°–140°E). (c), (d) Same as in (a) and (b), respectively, but for contribution from the fast annual cycle. Values greater than 6 mm day^{-1} are shaded in (a) and (b).Contour interval is 1 mm day^{-1} in (c) and (d), and minimum contours are +0.5 mm day^{-1} (solid) and −0.5 mm day^{-1} (dashed).

related with that in the following June indicates a continuity of the climate year of the coupled ocean–atmosphere system. The fact that all-India rainfall of June is uncorrelated with that of July–September (JAS) rainfall indicates that the biennial transition takes place between June and July. Based on these findings, they propose a slightly modified conceptual model monsoon year (Yasunari 1991; Yasunari and Seki 1992) for the coupled monsoon/atmosphere–ocean system as shown in Fig. 7. This schematic diagram depicts sequence two successive monsoon years, a year starting from the mid–late northern summer (JAS) and persists till early next summer (June). In the figure, a sequence of a "weak" monsoon year is shown followed by a "strong" monsoon year. The east–west Walker circulation is weakened associated with a weak monsoon and leads to colder SST in the western Pacific and warmer SST in the eastern Pacific in the following seasons (an El Niño condition). The colder SST in the western Pacific is crucial in maintaining anomalous ENSO state from winter until next June actively leading to a weaker Asian monsoon during early summer. The right side of the figure depicts the processes in a strong monsoon year. The strong convective activity during the mid–late summer leads to a cold condition in the eastern Pacific and a warm condition in the western Pacific during the following winter (a La Niña condition). The La Niña signal in the western Pacific carried by the ocean until the next June maintains a strong Asian monsoon in June.

Thus, there is evidence that air–sea interaction plays an important role in the observed TBO. However, it is not clear that air–sea coupling is essential for existence of the observed TBO. It may be noted that most coupled GCMs (CGCMs) that simulate TBO have a significant systematic bias in simulating the climatological mean AC. Systematic biases in simulating the climatological mean may play a significant role in simulating a TBO in many of these CGCMs. Hence, it is not well settled that air–sea coupling is essential for the existence of the TBO. It is possible that a TBO may be triggered by atmospheric internal dynamics but amplified through air–sea coupling. In section 6, we provide such a possibility as a counterexample.

In addition to the ENSO-related ocean–atmosphere interaction, local warm-ocean atmosphere interaction

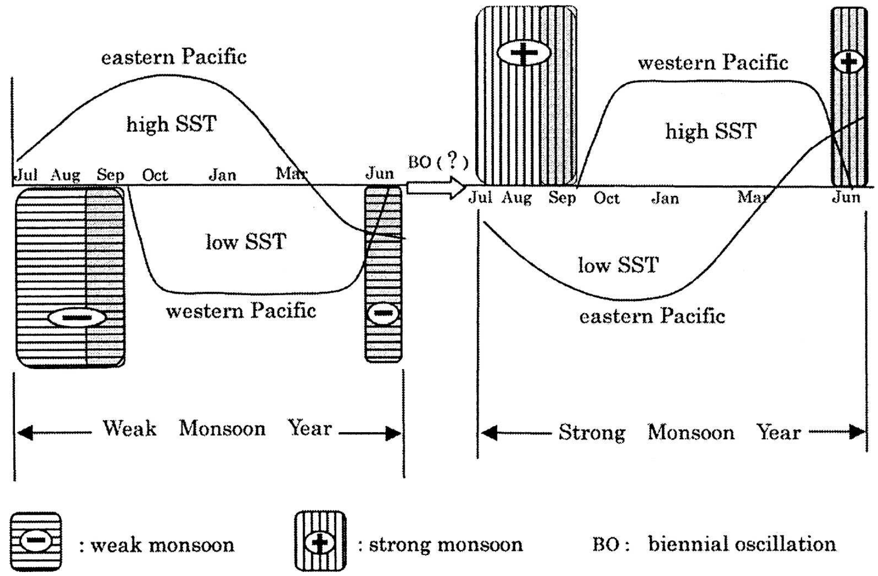

FIG. 7. Schematic diagram of two successive monsoon years for the coupled ENSO–monsoon system (from Ailikun and Yasunari 2001, © Meteorological Society of Japan).

over the IO and western North Pacific (WNP) can also give rise to IAV of the MAC. The recently discovered Indian Ocean dipole mode (Saji et al. 1999; Webster et al. 1999) is a good example of manifestation of such air–sea interaction. This mode is not an equatorially confined zonal mode. The SST dipole is coupled with the south IO anticyclonic anomalies. In the presence of the summer monsoon background flow, the ocean to the east of the anticyclone near Sumatra cools as a result of coastal upwelling, evaporation, and entrainment. Reduction of convection associated with the cooling excites westward-propagating descending Rossby waves and reinforces the anticyclone (Li et al. 2003; Wang et al. 2003). However, the role of the IO dipole mode on IAV of the south Asian summer monsoon is unclear at this moment. Similar warm ocean–atmosphere interaction involving the WNP anticyclone leads to IAV of the EAM (Wang et al. 2003).

We provide some empirical evidence that the observed MAC is modulated by the coupled ocean–atmosphere interaction. In Fig. 8a the amplitude of the AC of zonal winds from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996; Kistler et al. 2001) at 850 hPa averaged over 7°–17°N, 40°–80°E (U850) is plotted for 54 yr (1948–2002) together with Niño-3 SST anomalies (SSTAs) during JJA. The correlation between the AC of U850 and JJA Niño-3 SSTA is −0.53. This correlation is significant at better than the 99.9% level and indicates that the AC of U850 (which is related with the strength of the ASM) is modulated by the ENSO. In another example, anomalous AC of Indian rainfall is related with JJA Niño-3 SSTA in Fig. 8b over a much longer period between 1871 and 2000. The anomaly of all-India monthly rainfall (Parthasarathy et al. 1994) is obtained as departure of observed monthly means from a climatological monthly annual cycle. Anomalous AC is defined as the difference between the JJA mean anomaly minus the following DJF mean anomaly. The correlation between the two is −0.61 for the 130-yr period. The 21-yr sliding correlation between the anomalous AC of Indian monsoon rainfall and Niño-3 SSTA during JJA (Fig. 8c) indicates that even though the correlation between the two has decreased during the recent years it is still higher than that between JJAS Indian precipitation and ENSO (Kumar et al. 1999). Thus, the IAV of the AC of Indian monsoon rainfall is also strongly related with the ENSO.

4. IAV of the onset of a monsoon: Thermal effect of the Tibetan Plateau

The role of the TP thermal forcing on maintaining the MAC was mentioned in section 2. The TP thermal forcing also influences the IAV of the MAC by influencing the seasonal transitions (Hung et al. 2004; Yanai and Tomita 1998). Li and Yanai (1996) used the difference between 30° and 5°N of the upper-troposphere temperature to present the meridional land–sea thermal contrast between subtropics and Tropics and to study the Asian monsoon onset and maintenance. It

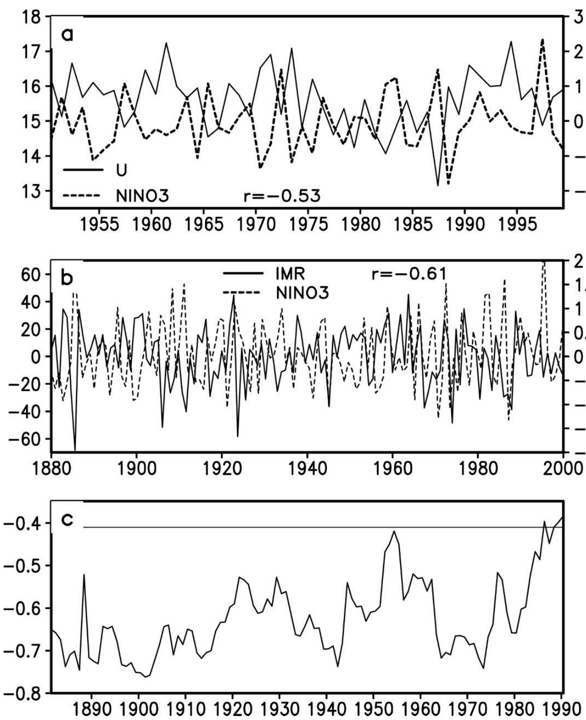

FIG. 8. (a) Amplitude of AC (JJA − DJF) of zonal winds at 850 hPa in the north central Arabian Sea averaged over 7°–17°N, 40°–80°E from NCEP–NCAR reanalysis between 1948 and 2002 (solid; scale on left in m s^{-1}) and Niño-3 SSTA during JJA (dotted; scale on right in °C). (b) Anomalous AC of precipitation over India between 1871 and 2000 and Niño-3 SSTA during JJA (dotted; scale on right in °C). (c) The 21-yr sliding window correlation between the two variables in (b).

may be noted that the reversal of the prevailing wind direction associated with the Asian monsoon onset occurs along the zonal-oriented ridgeline of the tropical–subtropical anticyclone, which is a narrow band between 30° and 5°N. During the monsoon onset, lower-troposphere westerlies cross the ridgeline and intrude into the lower-latitude area where easterlies predominate in the winter months, and the ridgeline moves southward rapidly. Therefore, to reveal the monsoon onset dynamics, it is insightful to study the thermal contrast across the ridgeline. It may also be noted that the ridgeline surface of the subtropical anticyclone can be well defined by the westerly–easterly boundary (WEB; where $u = 0$) that separates the midlatitude westerly from the tropical easterly. Subject to the thermal wind balance, the WEB always tilts toward the warmer region with increasing height. Therefore, the north–south temperature gradient reversal accompanied with the monsoon onset is manifested as a rapid change in the tilting of the WEB from southward in winter to northward in summer over the monsoon area. The perpendicular configuration of the WEB surface in this area then implies the seasonal transitions between winter and summer. The evolution of the WEB configuration during the seasonal transition over the Asian monsoon area is presented in Fig. 9 based on the NCEP–NCAR reanalysis and averaged between 1980 and 1998 together with outgoing longwave radiation (OLR). In April, while the whole WEB surface keeps tilting southward, such tilting becomes less and less over the eastern Bay of Bengal (BOB; Figs. 9a–d). In the first pentad of May (Fig. 9e), the sector between points D (90°E) and C (103°E) of the WEB surface becomes perpendicular to the earth's surface, indicating the occurrence of seasonal transition over the region and onset of the BOB monsoon (Mao et al. 2002a,b). Afterward point C propagates eastward quickly and reaches the eastern part of the South China Sea (SCS) by the fourth pentad of May (Fig. 9h). This corresponds to the SCS monsoon onset. Meanwhile point D moves slowly westward and reaches the west of the Indian subcontinent by early June, corresponding to the Indian monsoon onset. The above discussion concerns the climatological mean evolution, or MAC, of the Asian monsoon onset. It agrees with the finding of Wu and Zhang (1998) that the Asian monsoon onset composes three consecutive stages and the earliest onset occurs over the eastern BOB. Mao et al. (2002b) showed that the thermal contrast across the WEB is connected to the TP heating to the north and the thermal status of air over the Bay of Bengal to the south, with the former playing more important roles. This then provides the dynamical background for understanding the significant roles of the Tibetan Plateau heating in the IAV of the Asian monsoon onset.

The ISOs also play an important role in determining the IAV of the monsoon onset. In a detailed study of the Asian monsoon onset in 1989, Wu and Zhang (1998) stressed the importance of ISO in determining the three-stage feature of the Asian monsoon onset. They revealed that phase locking of an extratropical eastward-propagating 2–3-week oscillation in upper-tropospheric temperature and the rising phase of the northward-propagating divergent summer ISO over the East Asian monsoon region create the favorable condition for atmospheric overturning to take place over a large area and for the Asian monsoon onset. They also found that each of the three stages of the Asian monsoon onset is preceded by a rising surge of the surface temperature over the Tibetan Plateau. In a follow-up study, Zhang and Wu (1999) employed the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis between 1980 and 1989 to diagnose the temporal and spatial evolutions of the air temperature, general circulation, and surface heating during the

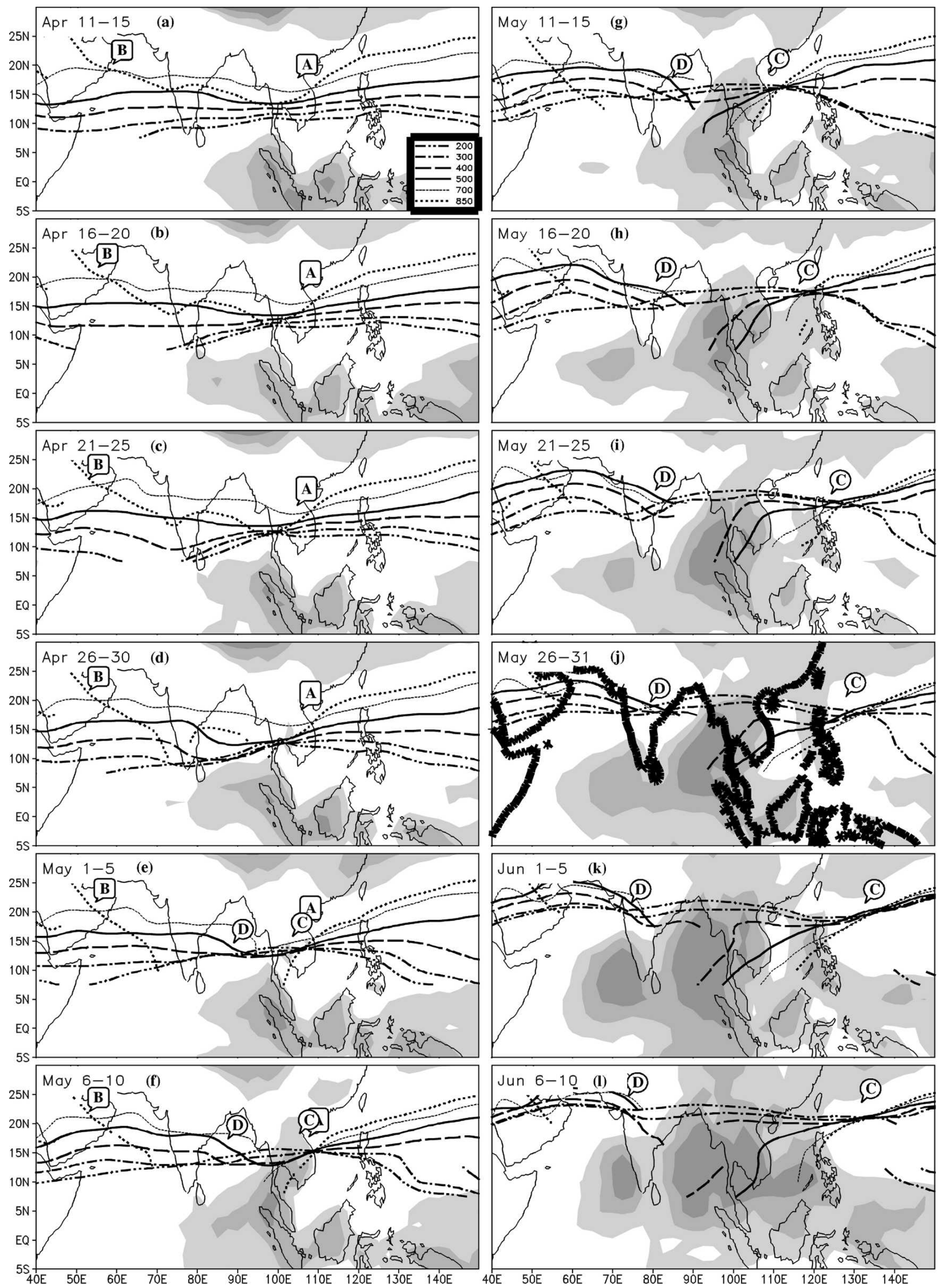

FIG. 9. The projection of the subtropical anticyclone ridgeline ($u = 0$) and OLR (W m^{-2}) at the levels from 850 to 200 hPa during the season transition (from the third pentad of April to the second pentad of June): (a) 11–15 Apr, (b) 16–20 Apr, (c) 21–25 Apr, (d) 26–30 Apr, (e) 1–5 May, (f) 6–10 May, (g) 11–15 May, (h) 16–20 May, (i) 21–25 May, (j) 26–31 May, (k) 1–5 Jun, and (l) 6–10 Jun. Light, heavy, and dark shadings indicate, respectively, the OLR values between 230 and 215, 215 and 200, and less than 200 W m^{-2}.

period from late spring to early summer over the Asian monsoon area. It was shown that each of the sequential onsets of the Asian monsoon coincides well with an abrupt increase of the air temperature over the Tibetan Plateau. Using the NCAR–NCEP reanalysis from 1951 to 1996, Zhang et al. (2002) investigated the MAC and IAV of the summer monsoon onset over the Indochina Peninsula. They confirmed that the monsoon onset is characterized by the pronounced northeastward progression of the low-level southwesterlies over the Indian Ocean and the intensification and northward extension of the tropical convection from Sumatra. It coincides with the westward propagation of the ISO originated from the South China Sea and the western Pacific. All these studies provide further evidence that the IAV of the Asian monsoon onset is significantly affected by the thermal status of the Tibetan Plateau and modulated by ISO.

As discussed above, the Indian monsoon onset is a result of the large-scale meridional pressure gradient in which the thermal heating over the TP plays a crucial role (Li and Yanai 1996). Here we present a new thermodynamic definition of the Indian monsoon onset in terms of meridional gradient of tropospheric temperature and compare with traditional monsoon onset over Kerala, India (MOK; Ananthakrishnan and Soman 1988a,b; Ananthakrishnan et al. 1967; Soman and KrishnaKumar 1993). We define a tropospheric temperature (TT) as an average of temperature between 200 and 600 hPa. Using daily NCEP–NCAR reanalysis data between 1950 and 2002, we calculate TT and define a TTN and TTS as averaged TT over a northern region (5°–35°N, 40°–100°E) and a southern region (15°S–5°N, 40°–100°E). Climatological evolution of TTN and TTS over the year is shown in Fig. 10a. We propose that large-scale Indian summer monsoon onset takes place when the TTN–TTS becomes positive. This marks the date when a clear large-scale tropospheric off-equatorial heat source is set up that drives cross-equatorial flow at lower atmosphere (above the boundary layer), makes the zero absolute vorticity line at lower atmosphere move to about 5° north of the equator, and triggers inertial instability (Krishnakumar and Lau 1998; Tomas and Webster 1997). The instability overcomes the inhibition associated with existing subsidence above the boundary layer and realizes the high convective potential leading to explosive development of off-equatorial convection, acceleration of low-level flow, and monsoon onset. It may be noted that the climatological mean onset date according to this criterion is 29 May (Fig. 10a), which is quite close to the climatologial mean MOK (2 June). Actual MOK dates were obtained from Joseph et al. (1994) and supplemented by dates published by the India Meteorological Department. The first times when TTN–TTS becomes positive are noted from NCEP–NCAR reanalysis data in terms of Julian days every year and are plotted against observed MOK dates in Fig. 10b. Strong correlation between the two (r = 0.67 for 53 yr) validates our hypothesis regarding the relationship between MOK and the change in sign of the meridional tropospheric

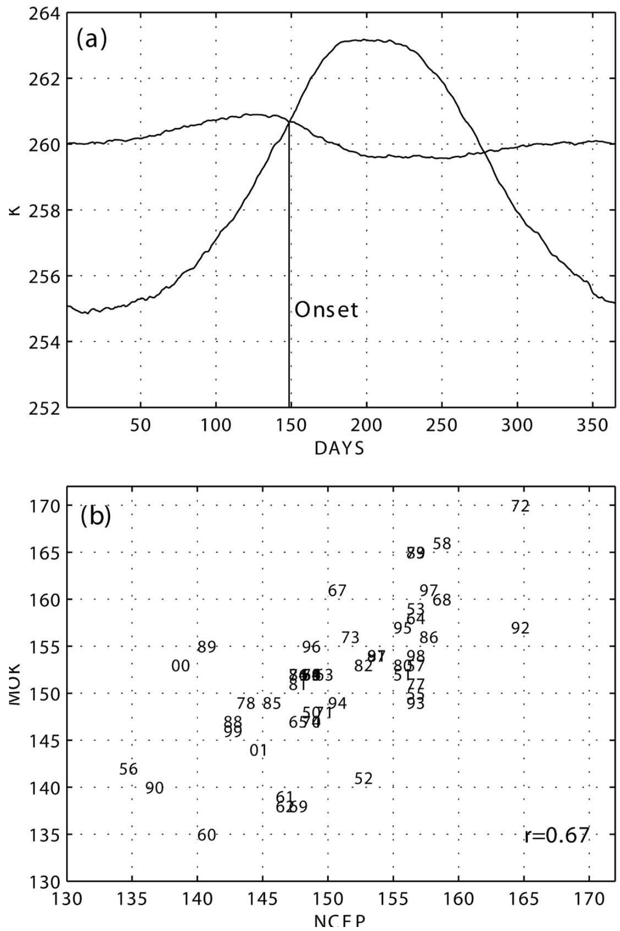

FIG. 10. TTN and TTS are TT averaged over a northern region (15°–35°N, 40°–110°E) and a southern region (10°S–15°N, 40°–110°E). (a) Climatological evolution of TTN and TTS over the year calculated from daily NCEP–NCAR reanalysis between 1950 and 2002. (b) Julian day of each year (1950–2002) when TTN becomes greater than TTS against corresponding MOK. Correlation between the two is shown.

heating gradient. Thus, the thermal status of the Tibetan Plateau during the premonsoon season has significant impact on the interannual variations of the MAC through changes in the seasonal transitions.

The IAV of the transition of meridional gradient of TT largely depends on IAV of TTN. Sensible heating from the surface of the Tibetan Plateau (depends on soil moisture and snow cover, etc.) has been shown to play an important role on IAV of temperature over the area and hence of monsoon onset (Li and Yanai 1996; Ueda and Yasunari 1998; Yanai et al. 1992). Recently, it has also been shown (Goswami and Xavier 2005) that both the onset and the withdrawal of the Indian monsoon could be influenced by the persistent TT anomaly forced remotely by tropical heating associated with the ENSO. An El Niño introduces a persistent negative TT anomaly over the TTN region and results in a late onset and early withdrawal of the monsoon. Thus, in addition to the local processes, the teleconnection associated with climate variability such as the ENSO can also influence the gradient of TT and hence the monsoon onset. The newly discovered teleconnection pathway is also helpful in understanding the physical connection between North Atlantic SST and the Indian monsoon (Goswami et al. 2006).

5. Scale interaction with monsoon ISO and IAV of the MAC

In addition to the external or slow processes that influence the MAC, described in the previous two sections, there are some internal or fast processes that could also influence the MAC and lead to IAV of the same. In this section, we illustrate one such process and demonstrate that interaction between the slow component of the climatological AC and the summer monsoon ISOs could impart significant influence on the MAC and cause appreciable IAV of the MAC. It may be recalled that the subseasonal variability of the Asian summer monsoon that shows up as active and break spells within the monsoon season is a manifestation of summer monsoon ISOs. The spatiotemporal structure of the summer monsoon ISOs has been studied extensively (see Goswami 2005, and references therein). Basic characteristics of the summer ISOs are very briefly summarized here. The temporal scale of the summer ISOs is larger than the synoptic time scale (>10 days) and smaller than a season (<90 days), within which two dominant time scales are prominent, one with periods between 10 and 20 days (Chatterjee and Goswami 2004; Chen and Chen 1993; Krishnamurti and Bhalme 1976) and another with periods between 30 and 60 days (Hartmann and Michelson 1989; Krishnamurthy and Shukla 2000; Krishnamurti 1985; Krishnamurti and Subrahmanyam 1982; Murakami and Nakazawa 1985; Sikka and Gadgil 1980; Yasunari 1979, 1980, 1981). The 30–60-day mode during northern summer has a large spatial scale similar in structure to that of the seasonal mean (JJAS) and leads to strengthening and weakening of the seasonal mean in its opposite phases (Annamalai and Slingo 2001; Goswami and Ajayamohan 2001; Krishnamurthy and Shukla 2000; Webster et al. 1998). In contrast, the spatial structure of the 10–20-day mode is rather regional in character (Annamalai and Slingo 2001; Goswami and Ajayamohan 2001). While the 30–60-day mode has a prominent poleward propagation over the ASM region, the 10–20-day mode is characterized by a westward phase propagation. Basic genesis and temporal and spatial scale selection appear to be of internal atmospheric origin involving convective feedbacks (Chatterjee and Goswami 2004; Gadgil and Srinivasan 1990; Goswami and Shukla 1984; Nanjundiah et al. 1992; Wang and Xie 1997; Webster 1983) but are modified by air–sea interactions (Fu et al. 2003; Rajendran et al. 2004; Sengupta et al. 2001; Waliser et al. 2004).

How do the ISOs influence the seasonal mean and its IAV? The ISOs could influence the seasonal mean if two criteria are fulfilled. First, the spatial structure of the dominant ISO mode should have significant projection on that of the seasonal mean, and second, the frequency of occurrence of the positive and negative phases should be asymmetric. If the spatial structure of the dominant ISO mode is similar to that of the seasonal mean and if the ISOs induced IAV of the seasonal mean, the spatial structure of the IAV of the seasonal mean and that of the ISO should also be similar (Palmer 1994). The possibility is tested with precipitation from NCEP–NCAR reanalysis. Precipitation data from NCEP–NCAR reanalysis between 1948 and 2002 are used in order to get enough statistics of interannual variability of the seasonal mean monsoon. Summer ISOs are extracted from 10–90-day filtered precipitation between 1 June and 30 September. A reference time series is created from 10–90-day filtered precipitation between 1 June and 30 September averaged over 10°–30°N, 70°–90°E. Active (break) days are identified from a reference time series normalized by its own standard deviation being greater than +1 (<−1). The spatial structure of the dominant ISO mode is shown in Fig. 11a, obtained from a composite of active minus break conditions from all years. The spatial structure of the IAV of Asian summer monsoon is shown in Fig. 11b, constructed from a composite of eight strong monsoon years minus eight weak monsoon years. The strong (weak) monsoon years are selected based on normalized JJAS rainfall averaged over 10°–30°N, 70°–90°E being greater than +1 (<−1). The similarity between the two patterns (pattern correlation is 0.74) indicates that the intraseasonal and interannual variations of the summer monsoon are governed by a common spatial mode of variability. Several earlier studies (Ajayamohan and Goswami 2000; Fennessy and Shukla 1994; Ferranti et al. 1997; Molteni et al. 2003; Sperber et al. 2001) have also noted that a common mode of spatial variability governs the interannual and intraseasonal variations of the Indian summer monsoon. We then ask whether the probability of occurrence of the positive and negative phases of intraseasonal variability of precipitation is distinctly different in strong and weak monsoon years. Frequency distributions of 10–90-day filtered precipitation anomalies be-

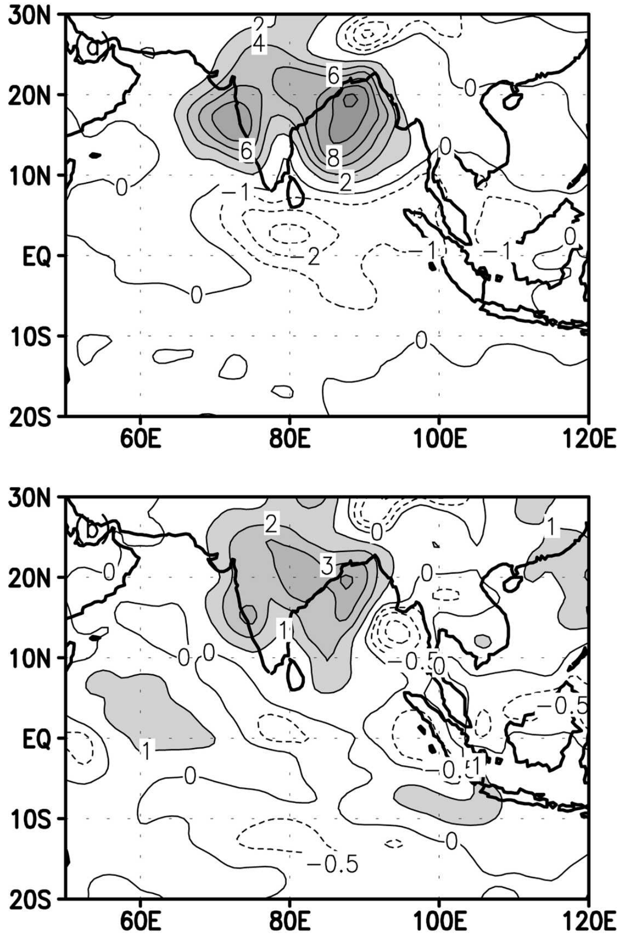

FIG. 11. (a) Spatial pattern of dominant ISO mode in precipitation (mm day^{-1}). Composite of all active minus break conditions, 10–90-day filtered precipitation between 1 Jun and 30 Sep for the period between 1948 and 2002. (b) Spatial pattern of dominant IAV of Asian monsoon. Composite of strong minus weak JJAS precipitation based on eight strong (1958, 1959, 1961, 1970, 1978, 1980, 1981, and 1994) and eight weak (1962, 1964, 1965, 1966, 1972, 1974, 1987, and 2002) years.

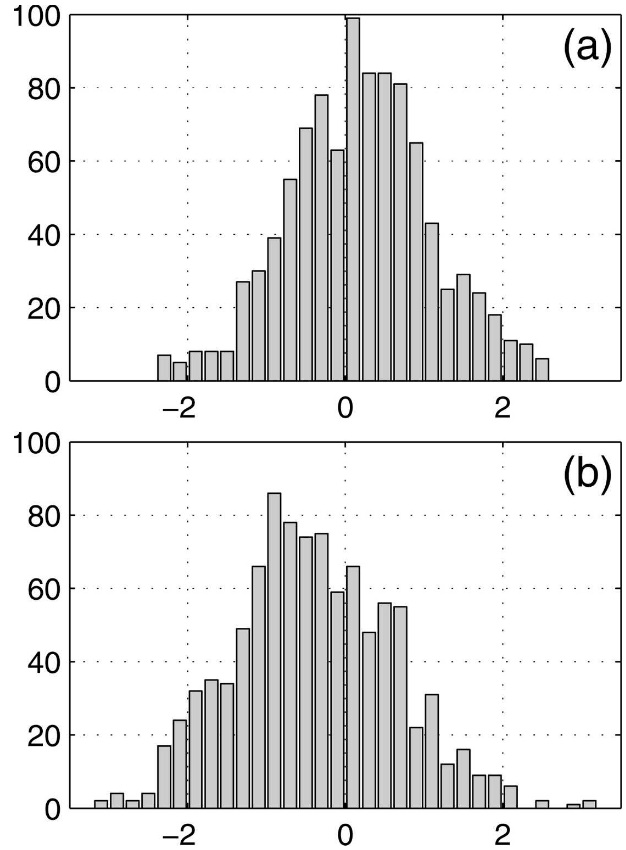

FIG. 12. Frequency distribution of 10–90-day filtered precipitation anomalies averaged over 10°–30°N, 70°–90°E for (a) eight strong monsoon years between 1 Jun and 30 Sep normalized by its own standard deviation. (b) Same as in (a), but for eight weak monsoon years from NCEP–NCAR reanalysis.

tween 1 June and 30 September averaged over 10°–30°N, 70°–90°E for eight strong monsoon years and for eight weak monsoon years are shown in Figs. 12a and 12b, respectively. The distribution is significantly biased toward the positive (negative) side of anomalies during strong (weak) monsoon years. The difference between the means of the two distributions is highly significant (at 99.9% confidence level using a two-tailed Student's *t* test). Thus, asymmetry in the frequency of occurrence of the active and break conditions is associated with stronger or weaker monsoons. This is essentially a quasi-linear mechanism in which the residual of the ISO anomalies over the season is well correlated with the seasonal mean. The aperiodicity or the broadband nature of the spectrum (10–90 days) of the ISOs is crucial for the asymmetry in the frequency of occurrence of the active/break conditions. The aperiodicity, in turn, arises due to nonlinear interactions among the dominant modes with higher-frequency disturbances. Thus, this mechanism implicitly involves some nonlinear interactions.

There is no doubt that the probability density function (PDF) of the summer ISOs determines the seasonal mean. However, a major debate continues on whether the modification of the PDF is entirely by external boundary forcing or partly by internal dynamics (independent of the external forcing). It is recognized that even in the absence of external forcing, the seasonal mean could be different from one year to another. Palmer (1994) first introduced the paradigm that the seasonal mean is determined by the PDF of the ISOs that are essentially of internal origin, but external boundary forcing could introduce IAV by modulating the PDF of the chaotic ISOs. Krishnamurthy and Shukla (2000) presented a modified form of the Charney and Shukla (1981) hypothesis for predictability of seasonal mean monsoon and indicated that the seasonal mean of a given year is a linear combination of the externally forced seasonally persistent component and a component coming from a shift of the PDF of ISOs due to internal dynamics. Krishnamurthy and Shukla (2000), through analysis of daily rainfall over India, and Sperber et al. (2000), from analysis NCEP–NCAR reanalysis data, examined this hypothesis and arrive at the conclusion that almost all IAV of the seasonal mean arises from slowly varying external forcing. However, both studies arrive at this conclusion from examination of the PDF of ISOs after removing the *total* IAV of seasonal mean from data. Both external forcing and internal dynamics introduce a shift of mean in the PDF. If the total IAV of the seasonal mean is removed from the data, it is rather obvious that the PDF of the ISO anomalies would be Gaussian. Unless a method is found to separate the contribution to the shift of the PDF due to external forcing from that due to internal origin, the question of contribution of pure ISOs to the seasonal mean could not be settled. A conceptual example of how internal dynamics could lead to change in the PDF of the ISOs and hence that of the seasonal mean is illustrated below.

In addition to the quasi-linear mechanism described above, there exists a nonlinear mechanism through which ISOs influence the seasonal mean and its IAV. Empirical evidence for such a nonlinear mechanism is obtained from the fact that the monsoon ISO activity is related to the MAC of precipitation and its IAV. Pentad precipitation from CMAP (Xie and Arkin 1996) for 23 yr (1979–2001) is used for this purpose and summer ISO activity is defined as the standard deviation of 10–90-day filtered (using a Lanczos filter) precipitation between 1 June and 30 September. The JJAS seasonal mean precipitation averaged over the region between 0°−30°N and 60°–100°E is plotted against summer ISO activity over the same region in Fig. 13a. Similarly, the amplitude of the AC of precipitation over the region, as defined by the difference between JJAS and DJF seasonal means, is plotted against summer ISO activity in Fig. 13b. The seasonal mean as well as the AC of precipitation over the monsoon region are well correlated with the amplitude of ISO activity. This result is consistent with the results of Waliser et al. (2004), who found that the amplitude of the AC of precipitation in AGCMs is closely related to the amplitude of ISO activity simulated by the AGCMs. This indicates that the nonlinearity of the ISOs is somehow related to the seasonal mean and IAV of the MAC. How does the nonlinearity of the ISOs lead to IAV of the MAC? Here, we propose that modulation of chaotic summer ISOs by

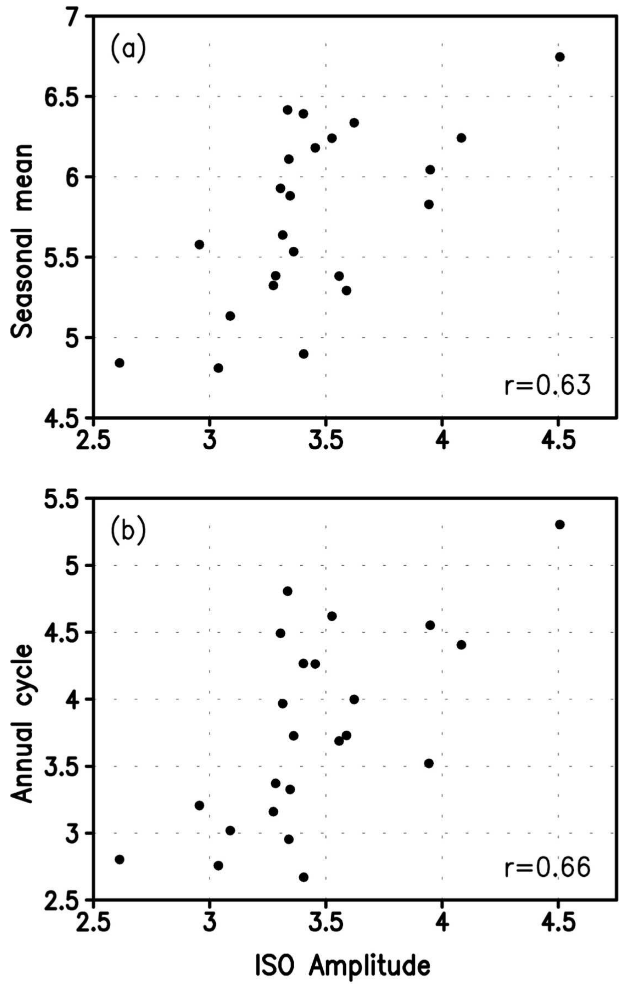

FIG. 13. Relationship between IAV of ISO activity in precipitation during northern summer (1 Jun–30 Sep) and that of (a) JJAS seasonal mean precipitation and (b) IAV of the AC (JJA minus DJF) of precipitation. Both quantities are averaged over 0°−30°N, 60°–100°E. Data used are CMAP between 1979 and 2002. ISO activity is defined as standard deviation of 10–90-day filtered precipitation. Correlations between the two are indicated in each panel.

annually varying forcing associated with the slow annual cycle can give rise to IAV of the AC. The feasibility of this hypothesis is demonstrated using a toy model. The model consists of a simple nonlinear dynamical system forced by annually varying forcing originally constructed by Lorenz (1984) to describe the general circulation of the atmosphere. The model is described by

$$\dot{X} = -Y^2 - Z^2 - aX + aF$$
$$\dot{Y} = XY - bXZ - Y + G$$
$$\dot{Z} = bXY + XZ - Z, \qquad (1)$$

where X may be interpreted as the zonal mean component while Y and Z may be considered as two wave

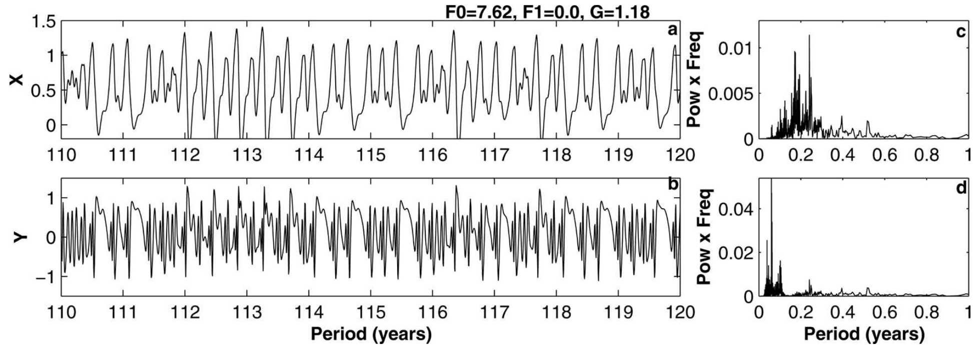

FIG. 14. (left) Time series of X and Y for constant forcing $F_0 = 7.62$, $F_1 = 0.0$, and $G = 1.18$ for a typical 10-yr period from a 200-yr simulation with (right) corresponding spectra. Power spectrum is plotted as power multiplied by frequency vs period.

components. The terms XY and XZ represent amplification of the waves through interaction with the mean flow and happen 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 representative of the land–ocean contrast. For fixed values of a, b, and G, different values of the solar forcing F lead to solutions of Eq. (1) that vary from periodic solutions with different periods to chaotic or aperiodic solutions for some values of F. In order that the nonlinear system represent the observed dominant ISO periods, the time in Eq. (1) has been scaled by a factor C (=0.57). The variables X, Y, and Z; the parameter a; and forcing F and G are also scaled appropriately. Using unscaled parameters, $a = 0.25$, $b = 4.0$, and $G = 1.18$, for $F = 7.62$, the solution is quite aperiodic (Figs. 14a,b) with dominant periods between 30 and 70 days (Fig. 14c) in X and 10 and 20 days in Y (Fig. 14d). The spectrum of oscillations represented by the model is representative of that of the monsoon ISO. The parameters were chosen following a method similar to one described by Lorenz (1984), so that the system has aperiodic solutions. 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 $F_0 = 5.6$ and $F_1 = 2.5$, the equations were integrated for more than 250 yr. Time series for X and Y for a typical 10-yr period and the corresponding spectra are shown in Fig. 15. It is seen that modulation of the intraseasonal oscillations by the annual cycle has resulted in a strong quasi-biennial oscillation (QBO) in both X and Y. The system goes to a regime 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 regime 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, modulation of the ISOs by the annual cycle could result in an internal IAV.

The mechanism through which the modulation of the nonlinear ISOs by the annual cycle forcing leads to IAV is as follows: The nonlinear system is chaotic only for some values of the forcing during the AC. For other values of the forcing, the system goes through various periodic regimes. For the forcing corresponding to the chaotic regime (corresponding to northern summer conditions), the attractor of the nonlinear system is a complicated "strange attractor" with several different folds in the phase space. As the forcing changes, the ISOs do not get a chance to explore the full phase space of the attractor during the summer season and map only a small part of the attractor. The seasonal mean is determined by the higher residence time of the ISOs during the summer season around one of the basins. Whether the system would reside more around one or the other basin depends on the initial condition with which it enters the chaotic regime. The initial condition with which the system enters the chaotic regime the next year (after coming out of the chaotic regime and after passing through the periodic regimes for the rest of the year) is different from that of the previous year and preconditions the system to reside around a different basin. This would give rise to a different seasonal mean for the next year. In the simple example, the chaotic regime visits two different basins facilitating a quasi-biennial IAV. If the process described above is correct, short-term integrations of Eq. (1) with different initial conditions should give different seasonal means. This was tested by integrating Eq. (1) for three months with parameters $a = 0.25$, $b = 4.0$, $G = 1.18$, and $F = 7.62$, for a large number of different initial conditions. It

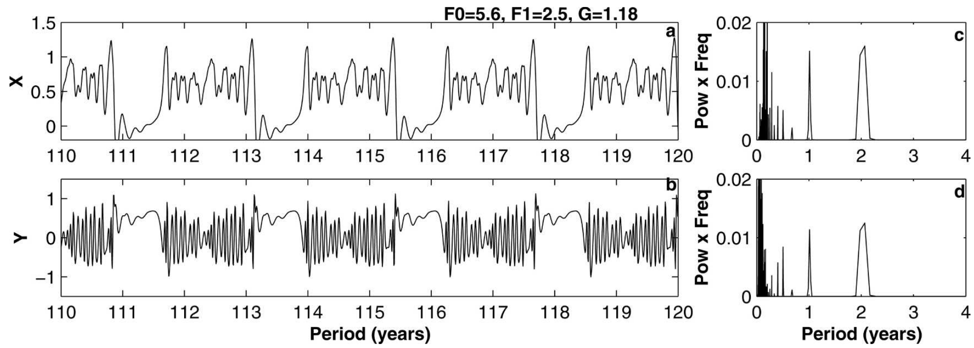

FIG. 15. Same as in Fig. 14, but for an annually varying forcing, F_0 = 5.6, F_1 = 2.5, and G = 1.18, that includes the chaotic regime shown in Fig. 17.

is found that for some initial conditions, the system (e.g., X) goes to a state of high mean with low-amplitude fluctuations while for another set of initial conditions, it goes to a state of low mean with high-amplitude fluctuations (figure not shown). Lorenz (1990) showed that a similar mechanism could give rise to year-to-year variation of extratropical climate where the flow is chaotic during winter rather than during summer as in the Tropics. Goswami (1995) investigated the origin of the tropospheric QBO using a model similar to Eq. (1) coupled to a low-frequency oscillator (representing the ENSO). The results from the toy model preset here indicate that the coupling to the low-frequency oscillator is not crucial and that modulation of the ISO by the annual cycle is sufficient to generate a tropospheric QBO.

6. Contribution of ISOs to internal IAV and their limit on monsoon predictability

The preceding discussions lend support to the fact that the monsoon ISO could lead to significant internal IAV of the seasonal mean monsoon. The important question, therefore, is how much of the observed IAV of the monsoon is governed by the internal component? Several recent studies have attempted to estimate the potential predictability of the summer monsoon by making estimates of internal variability from modeling studies (Cherchi and Navarra 2003; Goswami 1998; Kang et al. 2004; Molteni et al. 2003) and from observations (AjayaMohan and Goswami 2003). Almost all of these studies indicate that the contribution of the internal component to IAV of the summer monsoon is as large as or larger than that from the external component over the Asian monsoon region. We use zonal winds at 850 hPa from NCEP–NCAR reanalysis data for the period between 1979 and 2002 and estimate the internal variance of the monthly means during northern summer using the method described in AjayaMohan and Goswami (2003), and potential predictability is estimated as a ratio (Γ) between "total" interannual variance and internal variance and is shown in Fig. 16a. The predictability over the Asian summer monsoon region is poor, as the Γ ratio is less than or close to 2 over the region, indicating that the internal variance is comparable to or larger than external variance. A similar Γ ratio between the total interannual variance of the seasonal mean (JJAS) precipitation and the internal variance simulated by an AGCM [the Laboratoire de Météorologie Dynamique (LMD) GCM; Sadourny and Laval 1984] from a five-member ensemble simulation of 20-yr duration, all forced by observed SST as a boundary condition but differing only on initial conditions, is shown in Fig. 16b (Xavier et al. 2005, manuscript submitted to *J. Climate*). This figure also indicates that the Γ ratio for precipitation during northern summer (JJAS) over the Asian monsoon region is less than or close to 2. Thus, the Asian summer monsoon is a formidable system to predict as the predictable signal (external variance) is comparable to the unpredictable noise (internal variance) over this region. The internal variability of the seasonal mean largely arises partly from seasonal bias of ISO anomalies and from variability of ISO activity (not shown).

7. Conclusions and discussion

A conceptual framework is presented for examining the problem of predictability of the Asian summer monsoon. The framework starts with recognition that the Asian monsoon is associated with a strong AC and emphasizes that the ISOs are an integral part of the system and cannot be isolated from the annual AC. It is recognized that the climatological mean monsoon annual cycle (MAC) can be viewed in terms of superposition of a "slow annual cycle" and a "fast annual cycle." The fast annual cycle arising from the "climatological ISOs" indicates that the ISOs play an important role even in defining the climatological mean MAC. The summer monsoon ISOs are, therefore, an impor-

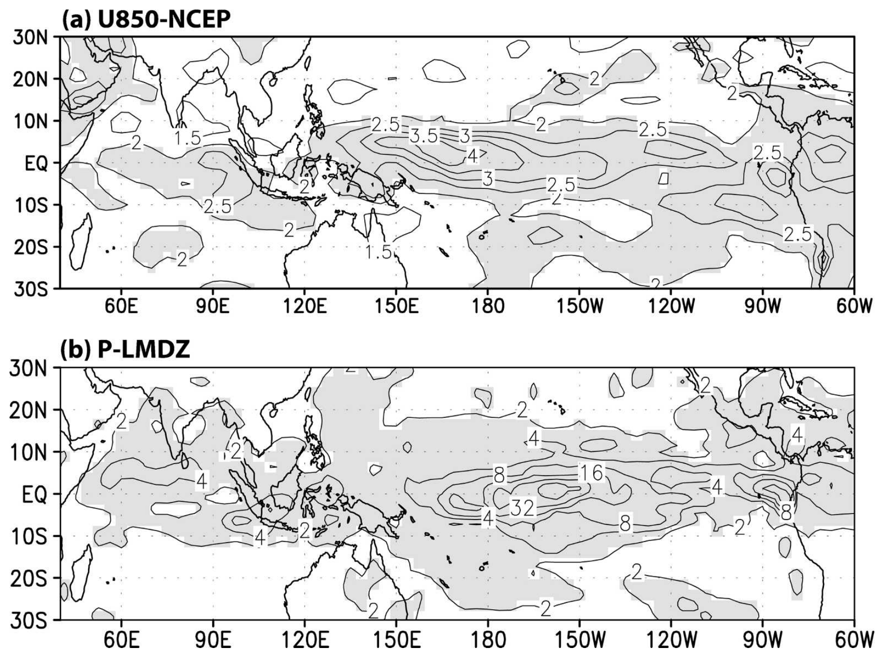

FIG. 16. Estimate of predictability for (a) zonal winds at 850 hPa and (b) precipitation during northern summer (JJAS). (a) Ratio (F) between total interannual variability of monthly means during JJAS and internal variability of zonal winds at 850 hPa based on daily NCEP–NCAR reanalysis data between 1979 and 2002. (b) Ratio (F) between total interannual variability of JJAS seasonal mean precipitation from a five-member ensemble of 20-yr simulation of LMD GCM and estimate of internal variability of the seasonal mean.

tant building block of the Asian monsoon system. The Asian monsoon is viewed as a nonlinearly interacting system of a MAC and chaotic summer ISOs.

The predictability of seasonal mean monsoon depends on IAV of the MAC. The IAV of the MAC, in turn, is governed by two distinctly different classes of processes. Slowly evolving coupled ocean–atmosphere oscillations modulate the MAC and so does slowly varying forcing associated with land surface processes such as TP heating, Eurasian snow cover changes, soil moisture changes, etc. Local warm ocean–atmosphere interaction can also give rise to IAV of the MAC. The IAV arising from these slow processes or "external" forcing is less sensitive to initial condition and more predictable. On the other hand, there is a fast process through which IAV of the MAC could take place. This occurs through nonlinear interaction between the MAC and chaotic summer monsoon ISOs. As the summer monsoon ISOs primarily arise from atmospheric internal dynamics and since the interaction through which this IAV is generated is intrinsically nonlinear, this "internal" part of IAV of the MAC is sensitive to initial condition and is hence unpredictable. Therefore, the predictability of the monsoon depends on relative contributions of the external and internal components to the total IAV of the MAC.

Processes that influence the climatological mean MAC and its IAV are reviewed. Empirical evidence that IAV of MAC is linked to air–sea interaction synonymous with ENSO is presented. It is shown that the dominant modes of IAV of the amplitude of the MAC of precipitation and low-level winds over the Indo-Pacific basin are closely correlated with ENSO. It is also shown that the timing of change in the sign of the difference between TT averaged over a northern box (10°–35°N, 30°–100°E) and a southern box (15°S–10°N, 30°–100°E) from negative to positive is strongly correlated with the date of onset of Indian summer monsoon over Kerala (MOK). While the meridional temperature gradient (or the pressure gradient) could be influenced by the monsoon heating itself after the summer monsoon is set up, the TP heating during the northern spring (April–May) has a seminal role in determining the gradient during the preonset time, influencing the onset phase of the MAC.

For over a decade, it has been recognized that the difficulty in predicting the summer monsoon either through empirical techniques or dynamical method using climate models is due to the existence of a significant amount of internal IAV of the Asian monsoon. However, a consensus on what is responsible for this internal IAV of the monsoon has not been reached. We propose here that the internal IAV of the monsoon is primarily due to interaction of the MAC and the ISOs. The ISOs do depend on the background condition set up by the slow component of the AC (external), but once activated can influence and change the seasonal mean and hence the MAC. Thus, ISOs represent an important player through which interaction with the AC gives rise to IAV of the MAC and sets up a limit to predictability of the monsoon. Consistent with some modeling studies, empirical evidence is provided showing that ISO activity is related to the amplitude of the annual cycle of precipitation. Using CMAP data during the period between 1979 and 2002, it is shown that the amplitude of AC of precipitation (JJA–DJF) over the Asian monsoon region is strongly correlated with ISO activity (standard deviation of ISO anomalies) during northern summer (June–September).

Two mechanisms through which ISOs modulate the MAC are discussed. The first of them works as follows: The spatial structure of the dominant summer ISO mode has significant projection on that of the summer mean and leads to the fact that the interannual and intraseasonal variations of the Asian summer monsoon are governed by a common mode of spatial variability. The spatial structure being similar, seasonal mean bias of the ISO anomalies leads to strengthening or weakening of the seasonal mean and hence that of the MAC. Nonzero seasonal mean bias of ISO anomalies is due to the fact that frequency distribution of intraseasonal anomalies during the summer season (June–September) is skewed toward the positive (negative) side during strong (weak) monsoon years.

The summer ISOs also produce IAV of the MAC through the following nonlinear mechanism: The large-scale flow associated with the slow annual cycle acts like an annually varying forcing for the ISOs. The ISOs are chaotic (nonlinear) for the forcing corresponding to the northern summer while they may be periodic (linear) for forcing corresponding to the rest of the year. The chaotic summer ISOs have a complex attractor with a number of different basins. The ISOs get to map only a small part of the attractor as the forcing change and chaotic regime could not be sustained at the end of the summer season. Higher residence time around one of the basins during the summer season determines the seasonal mean. Whether the ISO would reside more around one or the other basin during the season depends on the initial condition with which it enters the chaotic regime. The modulation of the chaotic ISOs by the slow annual cycle can, thus, lead to IAV of the seasonal mean or the MAC. This is essentially the source of the internal or unpredictable part of IAV of the monsoon.

It is clear that the asymmetry of the PDF of ISO anomalies contributes to the anomaly of the seasonal mean. A part of the asymmetry of the PDF may be due to modulation of the ISOs by external slowly varying forcing while the remaining part of asymmetry of the PDF is due to internal dynamics of the ISOs. Because of the interacting nature of the MAC, ISOs, and the slowly varying external forcing, it is rather difficult to separate the contribution from external forcing and internal dynamics to the asymmetry of the ISO PDF from observations. It remains to be an unsettled problem. Two observations (Fig. 17), however, indicate that internal dynamics may play a greater role in the asymmetry of the ISO PDF over the ASM region. First, summer ISOs seem to be somewhat decoupled from the ENSO forcing over this region. While the correlation between IAV of the standard deviation of ISO anomalies during JJAS with Niño-3 SST is quite large over the tropical Pacific, it is nearly zero over the ASM region (Fig. 17a). Second, the frequency distribution of normalized ISO anomalies between 1 June and 30 September averaged over 10°–30°N, 70°–90°E, for four non-ENSO strong monsoon years and four non-ENSO weak monsoon years, is still asymmetric (Fig. 17b, statistically significant). Assuming that non-ENSO strong or weak seasonal mean monsoon rainfall is essentially driven by internal dynamics, Fig. 17b indicates that internal dynamics could produce asymmetry of the ISO PDF. Various estimates of contribution of internal IAV to total IAV of the monsoon indicates that up to 50% or more of the observed IAV of the monsoon over the Asian monsoon regions could be attributed to internal variability. The fact that the predictable "signal" of the Asian monsoon is comparable to the unpredictable internal variability ("noise") makes it a most difficult system to predict. This results from a combination of two things. The amplitude of the external component of the IAV is weak over this region while that of the internal component generated by the ISOs is relatively large. Thus, the ISOs are, in a way, responsible for limiting predictability of the Asian monsoon. It may be noted here that there are other regions in the Tropics (e.g., the equatorial central Pacific) where the external forced component of IAV is much larger than that from internal variability and the climate is predictable (consistent with the Charney–Shukla hypothesis).

Such analysis also indicates that there are two important requirements for reasonable success in predicting the seasonal mean Asian monsoon. First, any model (AGCM or CGCM) attempting to predict the monsoon must be able to simulate the amplitude and spatial structure of the observed external component of the IAV (caused by air–sea interactions, TP heating, etc.)

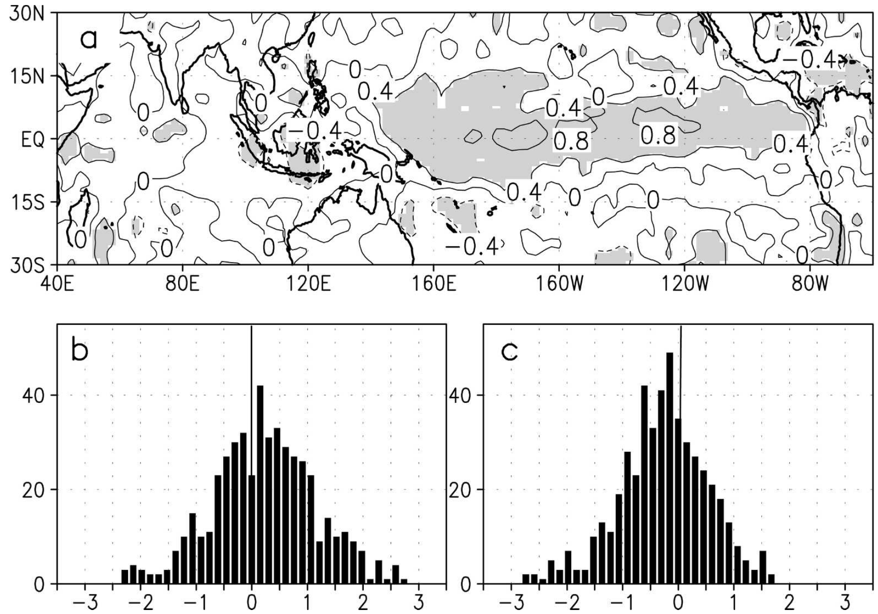

FIG. 17. (a) Correlation coefficient between IAV of standard deviation of 10–90-day filtered precipitation between 1 Jun and 30 Sep from CMAP (1979–2002) and JJAS mean Niño-3 SST. (b) Frequency distribution of 10–90-day filtered precipitation anomalies averaged over 10°–30°N, 70°–90°E for four non-ENSO strong monsoon years (1956, 1959, 1961, and 1994), between 1 Jun and 30 Sep normalized by its own standard deviation. (c) Same as in (b), but for four non-ENSO weak monsoon years (1968, 1974, 1985, and 2002) from NCEP–NCAR reanalysis. To get a reasonable number of non-ENSO strong (weak) monsoon years, the criterion for selection used is for the monsoon index to be greater than +0.5 (less than −0.5).

correctly. Since the amplitude of this signal is rather small over the Asian monsoon region, a small shift in simulating the spatial pattern could lead to a large percentage error for the simulated variability over the Asian monsoon region. Similarly, if the amplitude of the simulated external component by a model is systematically weaker than observed, the internal variability would have an undue advantage in making the monsoon unpredictable. A systematic diagnosis of simulation of this component of variability by the model is, therefore, required before embarking on prediction of the monsoon. The second requirement is that the model must be able to simulate the observed spatiotemporal characteristics of the summer ISOs with a certain degree of fidelity. For example, higher-than-observed amplitude of simulated summer ISO activity may result in higher-than-observed amplitude of simulated internal IAV of the seasonal mean and may adversely influence prediction skill. The structure and amplitude of the summer ISOs in a model depend on the hydrological cycle of the model governed, among others, by parameterization of convection and land surface processes in the model. Therefore, correct simulation of the summer ISOs involves complex interactions within the model framework.

It has come to light in the last couple of years that certain amounts of air–sea interactions are involved with the summer ISOs. Therefore, ideally a coupled ocean–atmosphere model would be desirable for correct simulation of the observed characteristics of the summer ISOs. However, the coupled models have their own systematic bias in simulating the mean climate. The systematic bias of the coupled model could influence the statistics of the simulated ISOs. Therefore, it is not obvious that a coupled GCM would automatically improve the simulation of the ISOs. However, air–sea coupling associated with the ISOs also raises an interesting issue. If the air–sea coupling introduces certain amount of constraint on the ISOs, would it also introduce constraint on the internal variability and possibly make it more predictable? Systematic studies by coupled and uncoupled AGCMs are required to answer these questions.

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