Thrusts and Prospects on Understanding and Predicting Asian Monsoon Climate*

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ABSTRACT

Development of monsoon climate prediction through integrated research efforts to improve our understanding of monsoon variability and predictability is a primary goal of the Asian Monsoon Years (2007–2011) and International Monsoon Study under the leadership of the World Climate Research Programme. The present paper reviews recent progress in Asian monsoon research focusing on (1) understanding and modeling of the monsoon variability, (2) determining the sources and limits of predictability, and (3) assessing the current status of climate prediction, with emphasis on the weekly to interannual time scales. Particular attention is paid to identify scientific issues and thrust areas, as well as potential directions to move forward in an attempt to stimulate future research to advance our understanding of monsoon climate dynamics and improve our capability to forecast Asian monsoon climate variation.

Key words: Asian monsoon, climate predictability, climate prediction, intraseasonal oscillation

1. Introduction

The giant Asian monsoon system embodies the most complex interactions between Earth's atmosphere, hydrosphere, cryosphere, and biosphere including human activities. The Asian monsoon interacts with the El Niño-Southern Oscillation (ENSO) and underlying oceans, resulting in far-reaching impacts on global climate and environment. Given the necessity of reducing uncertainty in global warming projections, understanding the dynamics of monsoon systems is of paramount importance.

The Asian monsoon variability significantly influences the economy and society across Asian countries, where about 50% of the world population inhabits. Any improved knowledge about monsoon rainfall variation and future change will be of great importance to sustainable development of world economy.

Monsoon science has advanced enormously in the last two decades. These advances have been comprehensively reviewed by leading scientists in the recent publications (e.g., Webster et al., 1998; Chang et al., 2005; Wang, 2006). Unprecedented amount of data derived from satellite observations and field experiments and the advance in improvement of climate models, computer power, and communication technology have deepened our understanding of the monsoon phenomena and enhanced operational capability in monsoon prediction.

Despite significant societal and environmental demands for accurate monsoon prediction and the notable improvements in our ability to simulate the Asian monsoon, operational prediction of Asian monsoon variations is still in its infancy and its achievement is seen as a great challenge faced by operational weather forecast centers worldwide.

It is imperative to improve Asian monsoon prediction through integrated research efforts to enhance our understanding of Asian monsoon variability and predictability. This is the main goal of the Asian Monsoon Years (AMY 2007–2011), which is a cross-cutting initiative as part of the International Monsoon Study (IMS) under the leadership of the World Climate Research Programme (WCRP).

This article reviews progresses in Asian monsoon research focusing on our capability in numerical

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modeling of climate variability and prediction of the prominent monsoon active/break periods and year-to-year fluctuations. Since increased knowledge in the Asian monsoon variability facilitates improvement of our modeling and predicting capability, the current understanding of the Asian monsoon variability will also be reviewed. Particular attention is paid to discuss major scientific issues and road blocks in an attempt to stimulate future research.

Section 2 discusses the monsoon responses to external solar forcing: the diurnal and annual cycles. Sections 3 and 4 deal with Asian monsoon variability, predictability, and prediction on the intraseasonal and interannual time scales, respectively. Different from the forced responses, the intraseasonal-interannual variations are due to internal feedback processes within the atmosphere and/or the coupled climate system. The last section briefly discusses some emerging modeling and prediction issues and future directions.

This review will emphasize precipitation−the most important variable for gauging the monsoon variability and making monsoon prediction. Precipitation is also one of the measures of the global water and energy cycle and holds a key in linking external radiative forcing and the atmospheric general circulation. Efforts are also made to merge the discussions of the knowledge and understanding with the discussions of modeling, predictability, and prediction.

2. Monsoon diurnal and annual cycles

Understanding and modeling the diurnal and annual cycles are essentially important for a number of reasons. Both the annual and diurnal cycles play significant roles in regulating monsoon variations in rainfall and circulation, thus affecting weather and climate fluctuations. The performance of numerical models in simulating seasonal mean states is closely related to their capability to predict seasonal anomalies (Sperber and Palmer, 1996; Slingo et al., 1996). Getting the annual cycle right is of critical importance for models to reproduce accurate teleconnection and climate anomalies away from the ENSO region (Bengtsson et al., 1993). The diurnal and annual cycles are also most relevant for revealing monsoon modeling problems because both of them have the largest amplitudes in the monsoon regions. Moreover, the diurnal cycles provide an efficient way for verification of models' physical parameterizations (Yang and Slingo, 2001). In practice, the onset and withdrawal of summer monsoons are of vital importance as agriculture and other human activities are strongly influenced by the period and/or duration of monsoon rainy season.

2.1 Observed diurnal cycle of precipitation

Monsoon regions exhibit the largest magnitude and most complex behavior of the precipitation diurnal cycles (Kikuchi and Wang, 2008). It has been recognized for a long time that strong diurnal variation of rainfall is a basic feature in the tropical land regions. However, only since the satellite era begins, the global as well as minute diurnal features of precipitation can be revealed (e.g., Murakami, 1983; Nitta and Sekine, 1994). Comparisons of satellite and gauge data have been conducted in Indo-China in the GAME project (Ohsawa et al., 2001) and over China (Yu et al., 2007). Recently, accumulation of the Tropical Rainfall Measuring Mission (TRMM) satellite observations has enabled to capture microscopic features of the diurnal variations over the entire tropics (e.g., Sorooshan et al., 2002; Nesbitt and Zipser, 2003).

Using two complementary TRMM datasets (3B42 and 3G68) for the 1998–2006 period, Kikuchi and Wang (2008) revealed that, in addition to the oceanic diurnal regime with an early morning peak in rainfall and the continental regime with an afternoon peak, there is a universal coastal regime in global monsoon regions, which shows strong rainfall movements, either inland or offshore. Figure 1 presents the evolution of the costal pattern in South Asia and maritime continent. Over South Asia, the inland propagation sets in along the coastline of India and the Indo-China Peninsula at 0900 LST and then becomes stronger and moves inland around noon (1200–1500 LST), peaking around 1500 LST; finally, the rain stops farther inland around 2100 LST. In the coastal offshore propagation, rain tends to start near the coast around midnight, expand over the ocean to 1200 LST, and then disappear between 1200 and 1500 LST. The results shown in

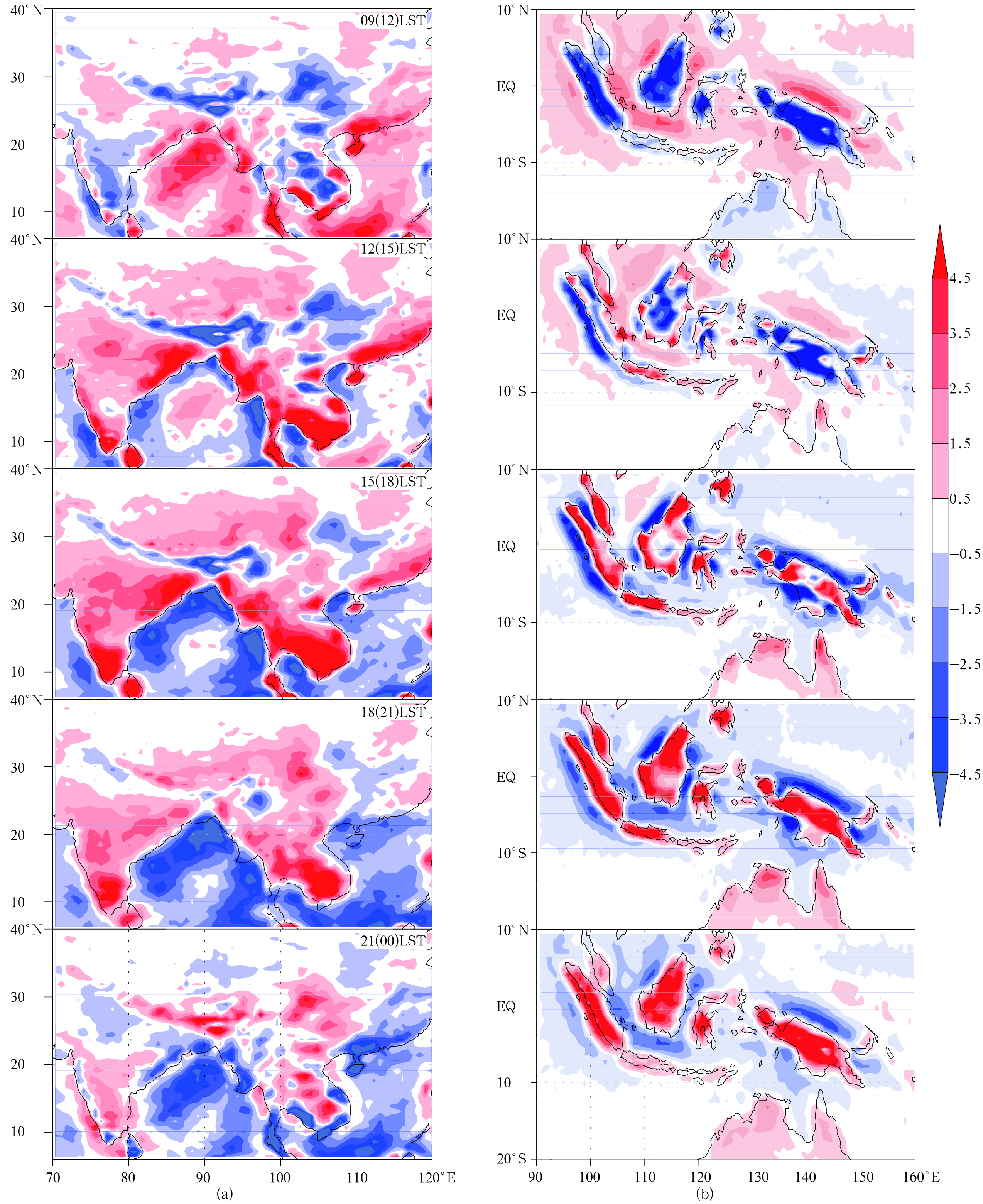

Fig.1. Evolution of precipitation diurnal cycle reconstructed from the first two extended EOF (EEOF) modes for (a) South Asia and (b) maritime continent. The corresponding modified (unmodified) local standard times are shown at the right corner of each subpanel. The fractional variances accounted by the two EEOF modes are shown in the titles. Modified from Kikuchi and Wang (2008).

Fig.1 provide a measure for gauging models' performance in simulation of the diurnal cycles.

Descriptions of the diurnal cycle using satellite data to date are primarily for clouds and rainfall; the related circulation and other fields have not been fully analyzed, except a few intensive observational analyses that provide detailed regional characteristics (e.g., Mori et al., 2004). We need to improve our understanding of the relationship between diurnal cycle and surface orography and land/sea configurations; the causes of the inland and offshore propagations of the diurnal cycle from coastal regions; the effects of the diurnal variation on the cloud/rainfall variations over the open ocean; and the interaction between the diurnal cycle and the intraseasonal oscillation (ISO).

2.2 Observed annual cycle of precipitation

Although conventional definition of the monsoon has been solely based on annual reversal of prevailing surface winds (Ramage, 1971), the monsoon climate is not only characterized by a change in surface winds, but also by its contrasting rainy summer and dry winter (Webster, 1987; Trenberth et al., 2000). The monsoon itself is a manifestation of the annual variation

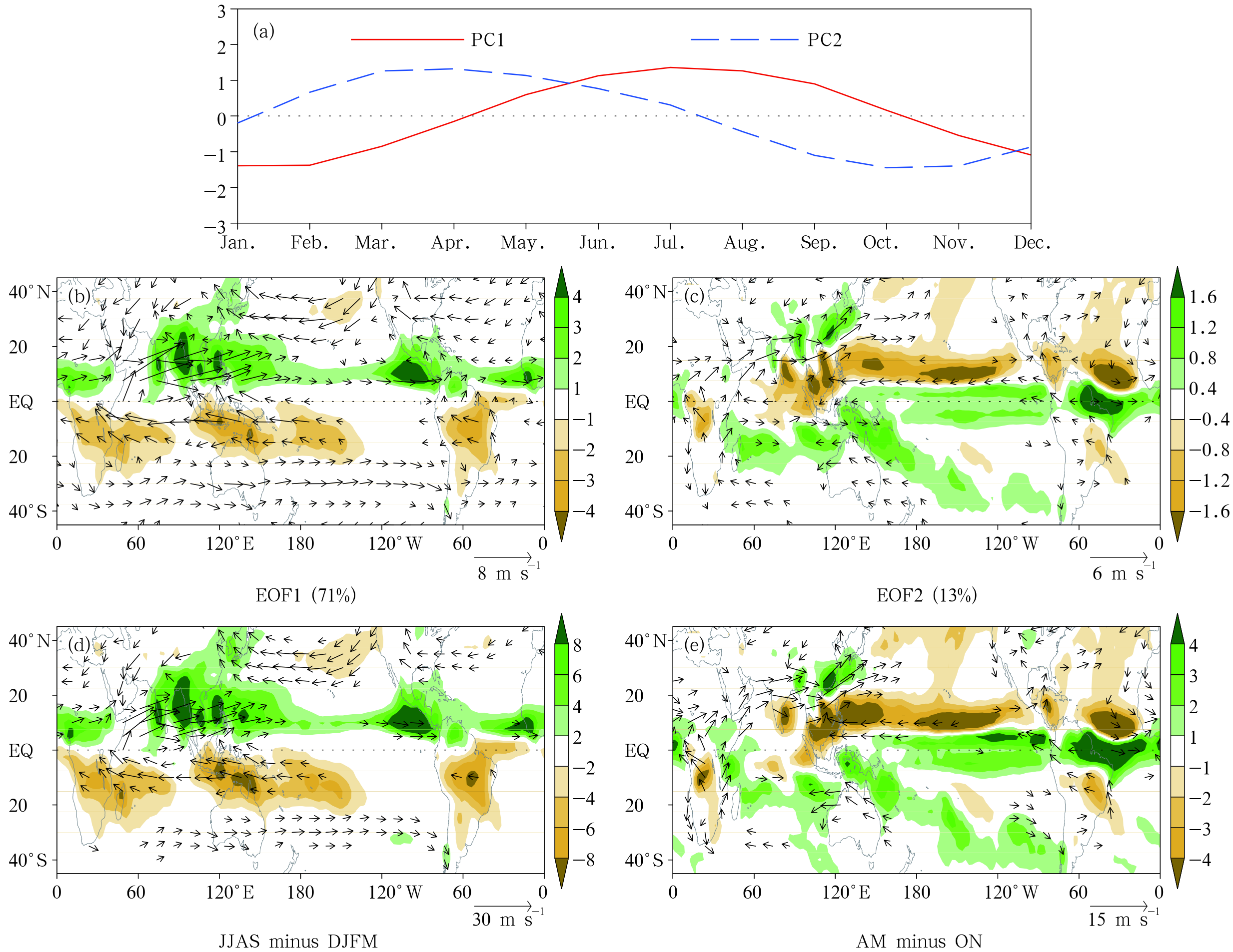

Fig.2. (a) Normalized principal components of the first two multi-variable EOF modes of the climatological monthly mean precipitation and the winds at 850 hPa. (b) and (c) are their corresponding spatial patterns of precipitation (shading, unit: mm day^{-1}) and winds (vectors in units of m s^{-1}) at 850 hPa for EOF1 and EOF2, respectively. Winds with wind speed of less than 1 m s^{-1} are omitted. (d) Solstice mode of the annual variation as described by the differential precipitation rate (mm day^{-1}) and the 850-hPa winds (namely, JJAS minus DJFM). (e) Equinoctial asymmetric modes as described by the April-May mean minus the October-November mean precipitation rate (mm day^{-1}) and the 850-hPa winds. Winds with wind speed of less than 4 and 2 m s^{-1} are omitted in (d) and (e), respectively. Modified from Wang and Ding (2008).

of the tropical general circulation (e.g., Webster, 1987; Zeng and Li, 2002).

Wang and Ding (2008) has shown that the global monsoon can be quantitatively defined by the first two empirical orthogonal modes of annual variation in global precipitation and low-level (850 hPa) winds (Fig.2). Both modes have an annual period (Fig.2a). The first mode features an interhemispheric contrast in precipitation (Fig.2b) and can be simply described as a June-July-August-September minus December-January-February-March precipitation pattern (Fig. 2d). Thus, the first mode is called the solstice mode, which reflects the impact of antisymmetric annual solar forcing with a one-to-two-month phase delay in atmospheric response. The second mode has the maximum and minimum occurring around April and October, respectively. Its spatial pattern (Fig.2c) resembles the April-May (AM) minus October-November (ON) precipitation and circulation pattern (Fig.2e). Therefore, the second mode represents an equinoctial asymmetric mode, or spring-fall asymmetry, which is one of the important features regarding the seasonal variation in tropical and monsoon circulation. As shown in Fig.2, the primary features of the annual cycle of tropical circulation can be quantitatively defined by a combination of the solstice mode and the equinoctial asymmetric mode; together, they account for 84% of the annual variance.

Although depiction of the rainy seasons over the land and islands has attracted numerous studies using rain gauge observations (e.g., Rao, 1976; Tao and Chen, 1987; Ding, 1992; Tanaka, 1992; Matsumoto, 1997), for a long time our knowledge has fallen short about the rainy season over the Asian marginal seas (such as the Arabian Sea, Bay of Bengal, South China Sea, and East China Sea). The precise seasonal march of the rainfall over Asia and adjacent oceans has been revealed only when accumulation of satellite derived proxy and global rainfall data are available (e.g., Wang, 1994; Lau and Yang, 1997).

Figure 3 shows that the large-scale onset of Asian monsoon rainy season starts from the Andaman Sea north of the Sumatera toward the end of April. The grand onset of Asian monsoon is characterized by the rainfall surges over the South China Sea (SCS) in mid-May, which establishes a planetary-scale monsoon rain

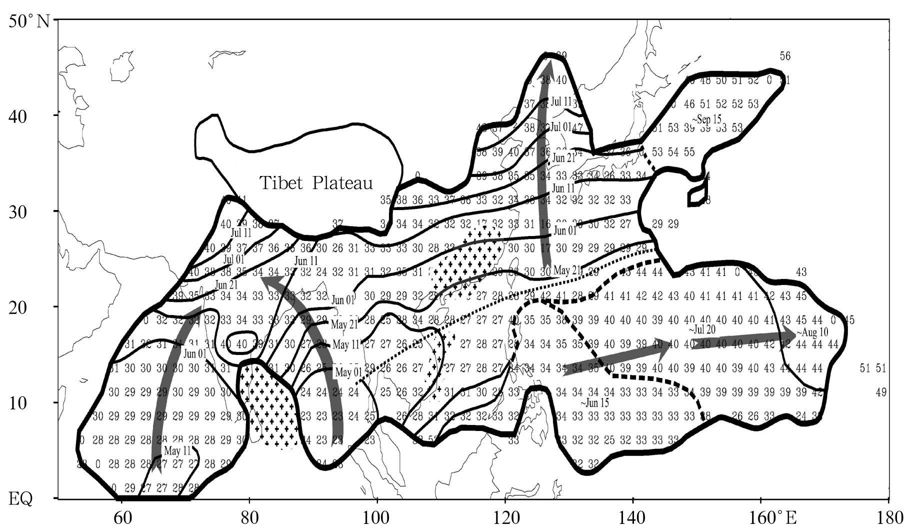

Fig.3. Dates of onset determined by relative climatological pentad mean (CPM) rainfall. The thick solid lines represent the Asian-Pacific summer monsoon domain defined by the maximum CPM occurring in boreal summer (May-September) and the annual range of the CPM exceeding the January mean rainfall rate by 5 mm day^{-1} (and the local January mean rainfall rate itself). The onset pentad is the first pentad when the CPM rainfall exceeds the January mean rainfall rate by 5 mm day^{-1}. The thick dashed lines denote discontinuities (merger of three or more contours). The arrows point to the directions of rain-belt propagation. The thin dashed line denotes the location of the subtropical monsoon front formation, which divides East Asian subtropical monsoon and tropical western North Pacific monsoon where their onset patterns are entirely different. Adopted from Wang and LinHo (2002).

band extending from the Bay of Bengal to the subtropical western North Pacific (WNP). The rain band then advances northwestward, initiating the continental Indian rainy season, the Chinese Meiyu, and the Japanese Baiu in early to mid-June.

It is not well understood why Asian monsoon first starts from the Andaman Sea and whether the monsoon onset is a manifestation of instability of the changing mean flow, or, it is caused by a finite amplitude disturbance that is formed after large scale mean flow is pre-conditioned. On the other hand, premonsoon rainfalls and latent heat release are seen in southern China (Tao and Chen, 1987; Ding, 2004), Indo-China (Kiguchi and Matsumoto, 2005) and over the Tibetan Plateau (Ueda et al., 2003; Taniguchi and Koike, 2007). The upper tropospheric heating is enhanced by such pre-monsoon rainfall events. How important these pre-monsoon rainfalls are and how they affect interannual variation of the monsoon onset are still open questions.

Although solar radiation forcing has sinusoidal variation, the seasonal cycle of the Asian monsoon often experiences stepwise, abrupt changes (e.g., Matsumoto, 1992; Ding, 1994, 2004; Ueda and Yasunari, 1996). The monsoon onset often occurs abruptly. For instance, Fig.3 shows a three-stage stepwise onset over the WNP. Wang and LinHo (2002) have shown that the heights of the rainy seasons occur primarily in three stepwise phases: in late June over the Meiyu/Baiu regions and the northern Bay of Bengal; in late July over India and northern China; and in mid-August over the tropical WNP. Another important aspect of the monsoon seasonal cycle is the asymmetric nature of the seasonal transition between boreal spring and autumn (Matsumoto and Murakami, 2002; Hung et al., 2004; Chang et al., 2005). In general, there is a need to identify the principal physical processes that determine the abrupt evolution in seasonal cycle, although the nonlinear atmospheric processes and the atmosphere-ocean interactions (Wu and Wang, 2001; Ueda, 2005) and land-atmosphere-ocean interaction processes (Minoura et al., 2003) have been hypothesized as the possible agents.

2.3 Numerical modeling of the diurnal and annual cycles

Accurate simulation and prediction of the spatial and temporal variation of diurnal rainfall around the globe remains one of the unsolved problems in climate system modeling. Sperber and Yasunari (2006) summarized the problems in the simulation by GCMs of the diurnal cycle. Adequate resolution of the planetary boundary layer, the coupling between the planetary boundary layer and deep convection may hold a key to the improvement of the diurnal cycle in GCMs.

What are the major weaknesses of the climate models in simulation of the annual cycle? Kang et al. (2002) found that all of 11 GCMs, which participated in the CLIVAR/Asian-Australian Monsoon Panel (AAMP) AGCM intercomparison project, overestimate the amplitudes of climatological seasonal variations of the Indian summer rainfall but underestimate the rainfall variation in the WNP. Recent evaluation of the 17 climate prediction models confirms that a common weakness lies in the WNP and East Asian monsoon region (Lee et al., 2008).

In the forced response of the monsoon, the following questions remain to be addressed: (a) What determines the structure and dynamics of the diurnal and annual cycles of the coupled atmosphere-ocean-land system? (b) How can the major weaknesses of climate models in simulation of the diurnal cycle and annual cycle of global precipitation be remedied?

3. Intraseasonal variability and predictability

The monsoon intraseasonal oscillation (MISO) is a dominant form of monsoon variability that links weather and climate. The MISO is closely related to the onset, active, and break periods of the monsoons. The Madden-Julian (1971, 1972) oscillation (MJO) has important impacts on MISO, but the behavior of the MISO is more complex than the MJO. This is in part due to the fundamental modification of the monsoon circulation on the MJO. In addition, the monsoon has its own intrinsic ISO modes (Krishnamurthy and Shukla, 2008). For instance, the

10–25-day modes and the independent northward propagating mode: about one half of the northward propagating ISOs over the Indian Ocean are independent of the equatorial eastward propagating MJO (Wang and Rui, 1990; Hendon et al., 2007).

3.1 Origin of the monsoon intraseasonal oscillation

The characteristics of the observed MISO have been extensively reviewed by Waliser (2006). It has been generally recognized that the MISO has the following essential features: (a) northward propagation in the Indian monsoon region (Yasunari, 1979, 1980; Sikka and Gadgel, 1980) and northwestward propagation in the WNP (e.g., Lau and Chan, 1986; Nitta, 1987; Hsu and Weng, 2001); (b) formation of a northwest-southeastward tilted anomalous rain band near Sumatera (Maloney and Hartmann, 1998; Annamalai and Slingo, 2001; Kemball-Cook and Wang, 2001; Lawrence and Webster, 2002); (c) initiation in the western equatorial Indian Ocean (60°–70°E) (Wang et al., 2005a, 2006; Jiang and Li, 2005), (d) the phase-locking to the annual cycle, or climatological ISO (CISO) (Nakazawa, 1992; Wang and Xu, 1997; LinHo and Wang, 2002), and (e) the prominent 10–25-day oscillation in the off-equatorial South Asian monsoon trough (Krishnamurti and Bhalme, 1976; Chen and Chen, 1993; Wu and Zhang, 1998; Wen and Zhang, 2008). In addition, the MISO has close interaction with ISOs in the mid-latitude region (Kawamura et al., 1996) and extratropical wave trains (Ding and Wang, 2007) due to its proxy to the subtropics.

Theories have been proposed to explain the essential features of the MISO. A review is provided in Wang (2005). The northward propagation has been explained in terms of boundary layer destabilization-convective stabilization (Webster, 1983; Goswami and Shukla, 1984), air-sea interaction (Kemball-Cook and Wang, 2001; Fu et al., 2003), and the effects of the monsoon easterly vertical shear (Jiang et al., 2004; Drbohlav and Wang, 2005). The formation of the NW-SE tilted precipitation belt has been interpreted as resulting from the emanation of convectively coupled equatorial Rossby waves from the decaying equatorial MJO disturbances (Wang and Xie, 1997; Lawrence and Webster, 2002). The re-initiation of the monsoon active-break cycles was attributed to local SST and hydrological feedback (Stephens et al., 2004) and a self-induction mechanism (Wang et al., 2005a, 2006). The role of the topographic effect of the maritime continent was also discussed by Hsu et al. (2004) and Hsu and Lee (2005).

However, the MISO involves multi-scale interactions among diurnal cycle, mesoscale and synoptic scale disturbances, the MJO and annual cycle. Full interpretation of the MISO phenomena remains elusive. Many issues invite further investigations, for instance: (a) What are the typical multi-scale and 3D structures of the MISO? (b) Are multi-scale interactions essential for development and maintenance of the MJO and MISO and if so how? (c) Why is there a 10–25-day oscillation and how is it related to the MISO? (d) How do we obtain a complete theoretical framework for describing the characteristics of the MISO? (e) What roles do atmosphere-ocean-land interactions play in sustaining the MISO? (f) To what extent and how does the ISV in SST depend on atmospheric forcing? And how does intraseasonal SST anomaly feedback to the ISO?

3.2 Modeling of intraseasonal variations

The realistic representation of tropical convection in our global atmospheric models is a long-standing grand challenge for numerical weather forecasts and global climate predictions (Waliser, 2006). The capability of models in reproducing the MJO and MISO has been continuously assessed over the last decade. Pertaining to the MISO simulations, Sperber et al. (2001) found that the AGCMs have difficulty in representing the pattern of precipitation associated with the dominant mode, and also the models usually fail to project the subseasonal modes onto the seasonal mean anomalies. Waliser et al. (2003b) analyzed the MISO in the 10 AGCMs that participated CLIVAR/AAMP AGCM intercomparison project and found that (a) the most problematic feature is the overall lack of variability in the equatorial Indian Ocean, (b) most of the model ISO patterns exhibit some form of northward propagation, but they often show a southwest-northeast tilt rather than the observed northwest-southeast tilt, and

(c) the fidelity of a model to represent boreal summer versus winter intraseasonal variability (ISV) appears to be strongly linked.

Why do AGCMs have considerable difficulties in simulation of the MJO and MISO? One of the major difficulties involves cumulus parameterization used to estimate the vertical redistribution of heat and moisture by unresolved convective clouds in GCMs (Slingo et al., 1996; Maloney and Hartman, 2001). In general, modeling of the ISO in the complex AGCMs must entail a series of parameterizations including moisture transport, clouds and convection, and radiation transfer; thus, uncertainties in mathematical descriptions of these multi-scale interactive parameterizations can jeopardize the model's capability in simulating the MJO (Wang, 2005). For instance, it is critical for models to get correct heating partitioning between convective and stratiform precipitation, yet AGCMs generally underestimate the portion of stratiform precipitation. The inadequate treatment of cumulus parameterization and the multi-scale interaction processes are the major hurdles for realistic simulation of MJO and MISO.

How to rectify systematic errors in models' simulation of the MJO remains a great challenge and many modeling issues remain unresolved. For instance, what are the roles of radiative heating and mesoscale systems in determining the heating profile (convective/stratiform) and how can this be correctly represented in models? How important is the modulation of the diurnal cycle in intraseasonal monsoon variations? How do the errors in simulating ISOs impact simulation of the interannual variability?

3.3 Predictability and prediction skills of MJO and MISO

The capability of daily weather forecast is limited by the chaotic nature of Earth's atmosphere and the growth of the initial errors (Lorenz, 1963) and useful weather forecast can be made only within a week or two. On the other hand, the statistical behavior of the weather averaged over a season may be predictable due to the persistent forcing from anomalous conditions at the sea surface and land surface (Charney and Shukla, 1981). The intraseasonal variability (ISV) falls between the daily weather and the seasonal mean climate. The ISV is largely governed by atmospheric internal dynamics (Palmer, 1994; Waliser et al., 2006) and is therefore, to a large extent, chaotic in nature and unpredictable. Fu et al. (2007) showed that air-sea coupling may extend ISV predictability, suggesting that atmosphere-ocean interaction may be a source of predictability for ISV. But in theory, the source and limiting factors for intraseasonal predictability remain elusive.

Based on the perfect model assumption, previous studies have suggested a theoretical forecast limit of ISO (potential predictability) out to 15 days for rainfall and to 30 days for upper level circulation field (e.g., Waliser et al., 2003b; Waliser, 2005; Liess et al., 2005; Fu et al., 2008; Pegion and Kirtman, 2008).

The estimated predictability and prediction skills of ISV were mostly made in terms of band-pass filtered MJO signals (a portion of ISV) or a portion of the MJO signals (the principal modes of the MJO). Using filtered data or principal modes for assess predictability/prediction skill are convenient but unconventional in comparison to assessing the weather and seasonal mean climate prediction. The true meaning of intraseasonal predictability and adequate metrics for assessing intraseasonal prediction remains to be rigorously defined.

About a decade ago, the dynamical forecast of the MJO by using the atmospheric only model of the vintage of the NCEP reanalysis had a useful skill only up to 9 days for boreal winter season (Hendon et al., 1999; Jones et al., 2000). However, dynamical models have improved significantly in the last decade (Sperber and Waliser, 2008) and in a few cases are able to predict the MJO out to a lead-time comparable to the empirical-statistical schemes (Seo et al., 2005; Kim et al., 2008; Vitart et al., 2008). Nevertheless, prediction of MJO is still in its infancy.

The prediction skills of the MISO have been assessed recently in the hindcast experiments made by DEMETER and APCC/CliPAS models (Kim et al., 2008). These models tend to considerably underestimate the intraseasonal variances over the WNP and

Indian monsoon regions. Only a few models can realistically capture the evolution and structure of the boreal summer ISO, such as the NW-SE slanted precipitation band. Although models have large systematic biases in the spatial pattern of dominant ISV, the leading EOF modes of the ISO in the models are closely linked to the models' ENSO, which is a feature that resembles the observed ISO-ENSO relationship.

4. Interannual variability and predictability

4.1 Causes of the year-to-year fluctuations

Webster (2006) and Yang and Lau (2006) provided comprehensive reviews on the interannual variability of the Asian monsoon. A great number of the monsoon literature has documented the year-to-year variability in various Asian monsoon regions, including the Indian monsoon (e.g., Mooley and Parthasarathy, 1984; Shukla and Mooley, 1987), the Indonesian monsoon (e.g., Yasunari and Suppiah, 1988; Hamada et al., 2002), the East Asian monsoon (e.g., Nitta, 1987; Huang and Wu, 1989; Li and Zeng, 2005; Zhou and Yu, 2005), and the WNP monsoon (e.g., Wu and Wang, 2000). The rainfall and circulation anomalies in many of the aforementioned regions exhibit a major 2–3-yr spectral peak (e.g., Meehl, 1987; Lau and Shen, 1988; Meehl and Ablaster, 2002). This is often referred to as the Tropospheric Biennial Oscillation (TBO) (Meehl, 1993).

Efforts have been made toward understanding the broad-scale interannual variability of the Asian-Australian monsoon (A-AM) system (e.g., Webster and Yang, 1992; Navarra et al., 1999; Miyakoda et al., 1999; Wang et al., 2003; Lau and Wang, 2006). Specific attention has been paid to the relationship between the ENSO and A-AM. Two principal modes of A-AM year-to-year variability have been identified (Wang et al., 2003, 2008c). The leading mode exhibits a prominent biennial tendency concurrent with the turnabout of ENSO, providing a new perspective of the seasonally evolving spatial-temporal structure for the TBO (Li et al., 2006). The second mode leads ENSO by 1 yr and is driven by SST anomalies associated with La Niña (Zhou et al., 2007).

The root causes of the interannual variation of the A-AM system have been extensively investigated over the past decade. The remote forcing from the ENSO through atmospheric teleconnection is no doubt an essential cause. But this is not the full story. For instance, the Indian monsoon rainfall variability appears to be determined by both the ENSO and equatorial Indian Ocean variability (Gadgil et al., 2004).

Since the SST anomalies in the monsoon ocean are, to a large extent, results of monsoon forcing, the monsoon-warm ocean interaction, rather than the warm ocean SST anomalies should be recognized as an essential process that determines the A-AM variability. The Indian-Ocean dipole (IOD) or zonal mode (Saji et al., 1999; Webster et al., 1999) is a beautiful example of the monsoon-ocean interaction. The IOD has impacts on monsoon rainfall anomalies in the Indian Ocean and over India and South Asia, East Africa, Maritime continent, East Asia, and the WNP (e.g., Saji et al., 1999; Guan and Yamagata, 2003). The processes supporting the IOD have been attributed to the equatorial Bjerkness positive feedback (Webster et al., 1999; Saji et al., 1999). The WNP anomalous anticyclone that affects East Asian summer monsoon is another persuasive example (Wang et al., 2000; Lau and Wang, 2006). The convectively coupled Rossby wave-SST feedback can maintain both the WNP anticyclone and SST anomaly, which provides a prolonged impact of ENSO on the East Asian summer monsoon even when the SST anomalies in the eastern Pacific disappears. Monsoon-ocean interaction can also provide an important negative feedback through monsoon-induced anomalies in the surface heat fluxes (Lau and Nath, 2000) or through the Ekman transport of ocean heat (Webster et al., 2002; Loschnigg et al., 2003). This negative feedback often offsets the impacts of the remote ENSO forcing, making the Indian summer monsoon more resilient to interannual variation and more difficult to predict. In addition, this negative feedback is potentially important for supporting the monsoon TBO (Webster et al., 2002).

There is a hidden factor that contributes to the A-AM variation but has often been neglected. The monsoon basic flow not only regulates the nature of atmosphere-ocean interaction (Nicholls, 1983), but also significantly modifies the monsoon response to remote ENSO forcing (Wang et al., 2003). Thus, the ENSO forcing, the monsoon-warm pool ocean interaction, and the influence of the annual cycle of the basic monsoon flow are three fundamental factors for understanding the behavior of the leading modes of A-AM variability (Wang et al., 2003).

The effects of the soil moisture and snow cover have long been recognized as sources of Asian monsoon variability, especially for the rainfall over the continental monsoon regions (see Yasunari (2006) for a detailed review). Yasunari (1991) and Dirmeyer et al. (1999) pointed out that the land surface conditions in spring have an impact on the following summer monsoon. The spring snow cover has shown to affect summer monsoon (e.g., Bamzai and Shukla, 1999; Zhang et al., 2004). But the role of the Eurasian snowfall does not overwhelm the SST impacts (Shen et al., 1998) and the snowfall itself may be affected by ENSO (Yang, 1996). The influence of snow cover and related soil moisture anomaly on the temperature and circulation anomalies in the lower troposphere may be limited to when and where the snow cover exists seasonally (Robock et al., 2003). More studies are needed to understand how snow in the Eurasian continent and/or over the Tibetan Plateau can affect succeeding monsoon activity.

In summary, our current understanding of the causes of the Asian monsoon interannual variability suggests that modeling and prediction of monsoon requires coupled atmosphere-ocean-land models; and an accurate forecast of the Asian monsoon requires realistic modeling of the ENSO, the annual cycle, the teleconnections associated with ENSO, the warm ocean-monsoon interaction, and the atmosphere-land surface interaction. These requirements make the modeling and dynamic prediction of Asian monsoon extremely challenge.

4.2 Modeling of monsoon interannual variations

Intercomparison of the capability of AGCMs to reproduce interannual monsoon anomalies has been one of the major efforts in identifying common problems of the models. Sperber and Palmer (1996) examined 32 AGCMs that participated in the AMIP project. They found that the Webster and Yang (1992) index (vertical wind shear) was better simulated than the all-Indian rainfall and that interannual variation was better simulated in the models which were able to generate a better climatology.

In assessment of the performance of 10 AGCMs that participated in the CLIVAR/AAMP AGCM intercomparison project, Wang et al. (2004) found that the models' poor simulation of anomalous summer monsoon rainfall is mainly due to lack of skill over Southeast Asia and the WNP region (5°–30°N, 80°–150°E). They proposed that the neglect of air-sea interaction is a major cause of the AMIP-type of models' failure. Examination of 5 AGCM-alone 21-yr ensemble simulations confirms that the AGCMs, when forced by observed SST, are unable to simulate Asian-Pacific summer monsoon rainfall (Wang et al., 2005b). The models tend to yield positive SST-rainfall correlations in the summer monsoon region that are at odds with observations. The observed negative SST-rainfall relationship (and rainfall leads SST variation) indicates atmosphere plays an active, not passive role. Thus, treating the atmosphere as a slave to specified SSTs may prohibit accurate simulation of summer monsoon rainfall anomalies.

Development of an effective strategy for improving models requires better design of the metrics for quantitative assessment of model performances and identification of the key modeling issues.

4.3 Predictability and seasonal prediction skills

In the past two decades, climate scientists have made ground-breaking progress in dynamic seasonal prediction. The advent of dynamic climate prediction can be traced back to El Niño forecast that used an intermediate-complexity coupled ocean-atmosphere model (Cane et al., 1986). Two types of prediction systems have been developed since the early 1990s. Bengtsson et al. (1993) proposed a "two-tier" approach for dynamical seasonal forecast, in which the global SST anomalies are first predicted, and an AGCM is subsequently forced by the pre-forecasted

SST to make a future seasonal prediction. While the two-tier approach was a useful strategy to capture better teleconnection, recent research advances suggest that prediction of certain phenomena (e.g., summer monsoon precipitation) requires taking into account local monsoon-ocean interactions (Wang et al., 2004; Wu and Kirtman, 2005; Kumar et al., 2005). Toward the end of the 20th century, a new era of seasonal forecast with CGCMs (also known as the one-tier approach) began, due to rapid progress made in coupled climate models (Latif et al., 2001; Davey et al., 2002) and due to a concerted international effort (through the Tropical Ocean-Global Atmosphere program) to monitor tropical ocean variations. Although the CGCMs still have significant systematic errors, many have demonstrated their capacity to reproduce realistic characteristics of ENSO (e.g., Latif et al., 1994; Ji et al., 1994). It has been increasingly recognized that the CGCMs are the ultimate tools for seasonal prediction.

For the two-tier systems, the physical basis for seasonal prediction lies in slowly varying lower boundary forcing, especially the anomalous SST (as well as the land surface) forcing (Charney and Shukla, 1981; Shukla, 1998). For the one-tier systems, prediction of ENSO and associated climate variability is essentially an initial value problem (Palmer et al., 2004). The slowly varying lower boundary of the atmosphere is evolving as a result of feedback from the atmosphere. The climate predictability in nature and in CGCMs comes from "slow" coupled (atmosphere-ocean-land-ice) dynamics and initial memories in ocean and land surfaces (Palmer et al., 2004; Wang et al., 2008b). Pertaining to the Asian monsoon, we need to find out how predictable the A-AM interannual variability is, especially in the continental monsoon region.

There are two types of error sources of dynamic seasonal prediction: atmospheric chaotic dynamics and uncertainties in the model parameterizations of unresolved sub-grid scale processes (Shukla et al., 2000; Kang and Shukla, 2006). Since the seasonal predictability does not depend on atmospheric initial conditions, an ensemble forecast technique with different atmospheric initial conditions was developed to reduce the errors arising from atmospheric chaotic dynamics. To alleviate the uncertainty arising from the sub-grid scales, stochastic physics schemes have been developed for individual models (Buizza et al., 1999). Meanwhile, a more effective way, the multi-model ensemble (MME) approach, was designed to reduce and quantify forecast uncertainties due to model formulation (Krishnamurti et al., 1999, 2000; Doblas-Reyes et al., 2000; Palmer, 2000). The idea behind the MME lies in that if the parameterization schemes in a group of models are independent of each other, the model errors due to the parameterization schemes may be random in nature; thus, an average approach may cancel out, at least partially, these errors.

It has firmly established that MME prediction is superior to the predictions made by any single-model component (Krishnamurti et al., 2000; Barnston et al., 2003; Doblas-Reyes et al., 2005). Based on this, a number of international projects have organized multi-model intercomparison and synthesis, among which the most comprehensive ones are the European Union-sponsored "Development of a European Multi-model Ensemble System for Seasonal to Inter-Annual Prediction (DEMETER; Palmer et al., 2004) and the Climate Prediction and its Application to Society (CliPAS) sponsored by the Asian-Pacific Economic Cooperation (APEC) Climate Center (APCC) (Wang et al., 2008a).

Recent evaluation of a 21-yr hindcast of 10 coupled climate models from the DEMETER and CliPAS shows that the one-month lead predictions capture the first two leading modes of variability with a verisimilitude that is at least comparable to or even better than that of the ERA-40 and NCEP-2 reanalyses (Wang et al., 2008a). This is due to the use of the multiple models and due to the fact that models include ocean-atmosphere interaction processes.

Wang et al. (2008b) assessed the current status of MME deterministic and probabilistic seasonal prediction based on 25-yr (1980–2004) retrospective forecasts performed by 14 APCC/CliPAS climate model systems (7 one-tier and 7 two-tier systems) and 7 DEMETER models' MME for the period of 1981–2001. Figure 4 shows that the forecast of monsoon

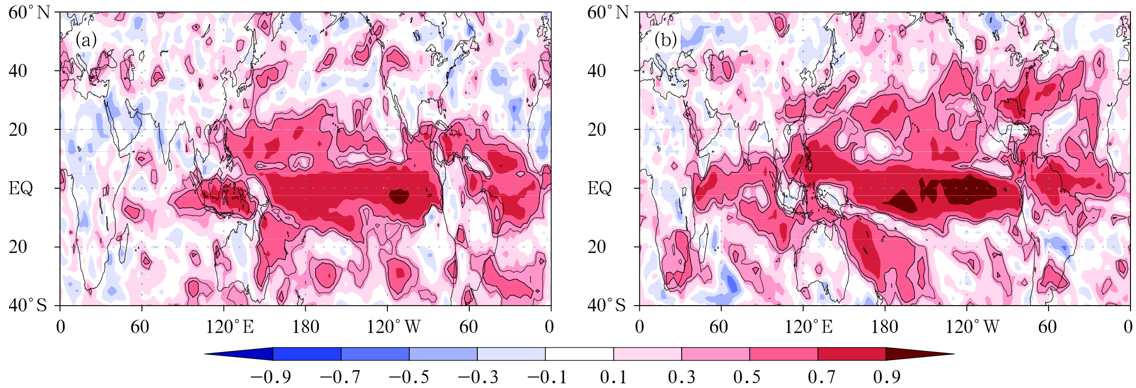

Fig.4. Temporal correlation coefficients for precipitation between observation and one-month lead seasonal prediction for 1981–2003 obtained from 14 APCC/CliPAS models' MME system in (a) JJA and (b) DJF, respectively. The thin (thick) solid contours represent statistical significance of the correlation coefficients at 0.05 (0.01) confidence level. Adopted from Wang et al. (2008b).

precipitation remains a major challenge; and the seasonal rainfall predictions over land and during local summer have little skill. The precipitation forecast skill averaged between 30°S and 30°N decreases away from the central-eastern Pacific, with the highest mean skill exceeding 0.5 found near the dateline (150°E–170°W) in JJA and from 150°E to 140°W in DJF; in contrast, the lowest skill is found over the tropical Africa.

5. Prospects on monsoon climate prediction

5.1 Seasonal prediction

Given the current levels of the climate models, a critical question is how we can get the best forecast through the MME. It has been speculated that the highest MME skill may be achievable by an optimal choice of a subgroup of models, drawing upon an individual model's skill and the mutual independence among the chosen models (Wang et al., 2008b).

While the MME is a proven approach that provides superior skill over any individual model, the skills of MMEs depend on having good models. Thus, improvement of individual models is of central importance for better climate forecasts. Then, what are the priorities we should take to improve climate models' physics?

The foremost factor leading to successful monsoon seasonal prediction is the model's capability to accurately forecast the amplitude, spatial pattern, and detailed evolution of ENSO cycle, because ENSO is the primary source for the monsoon and global climate predictability. This is particular true for a long lead seasonal forecast, because as forecast lead time increases, the model forecast tends to be determined by the model ENSO behavior (Jin et al., 2008). Therefore, Continuing improvement of the slow coupled dynamics in reproducing a realistic ENSO mode is a key for long-lead seasonal forecast.

The differences in the forecast skills over land areas between the CliPAS and DEMETER MMEs indicate potentials for further improvement of predictability over land (Wang et al., 2008b). The fact that MME has little skill in predicting precipitation over the continental region and during local summer season suggests potential importance of atmosphere-land interaction, because in these models the land surface initializations have considerable errors. There are urgent needs to (a) assess the impact of land surface initialization on the skill of seasonal and monthly forecast using a multi-model framework, (b) understand the roles of land surface processes and atmosphere-land interaction play in short-lead monthly and seasonal prediction, and (c) know how to improve seasonal prediction in continental monsoon regions.

Since the teleconnection both within the tropics and between the tropics and extratropics is a major source of predictability for the region outside of the eastern tropical Pacific, and since teleconnection is sensitive to mean climatology, continuing improvement of the mean state and seasonal cycle as well as statistical behavior of the transient atmospheric circulation in coupled models is also of importance (Wang et al., 2008b). However, to what extent seasonal predictions depend on nonlinear rectification of high-frequency atmospheric and oceanic processes (so-called "noises") is not well known.

In the current CGCMs, lack of land surface initialization and use of fixed sea ice are common. Since the primary memory affecting slow coupled dynamics is stored in ocean subsurface layers (Rosati et al., 1997) and land surfaces, continuing improvement of coupled model initialization is an urgent task. In addition, accurate description of the warm pool ocean-monsoon interaction is another key issue.

Inclusion of anthropogenic (especially aerosols) and natural forcing (solar, volcanic, and aerosol) and a better representation of sea-ice may also benefit accurate seasonal forecast.

5.2 Intraseasonal prediction

Prediction of the occurrence of large-scale droughts and floods as ahead as possible is of considerable practical values for a wide range of interests, especially for the management of environmental and financial resources. The MJO and MISO strongly modulate occurrence of the tropical cyclones and floods and droughts. Thus, prediction of MJO and MISO has great potential to meet the societal demand.

First, future improvement of the intraseasonal forecast relies on improved climate models. Numerical experiments with the global cloud-system resolving model (GCRM) developed at the Frontier Research Center for Global Change (FRCGC) have demonstrated the promise of very high resolution modeling in simulating multi-scale structure of the MJO (Nasuno et al., 2007). Using the GCRM that allows direct coupling of the atmospheric circulation and clouds, Miura

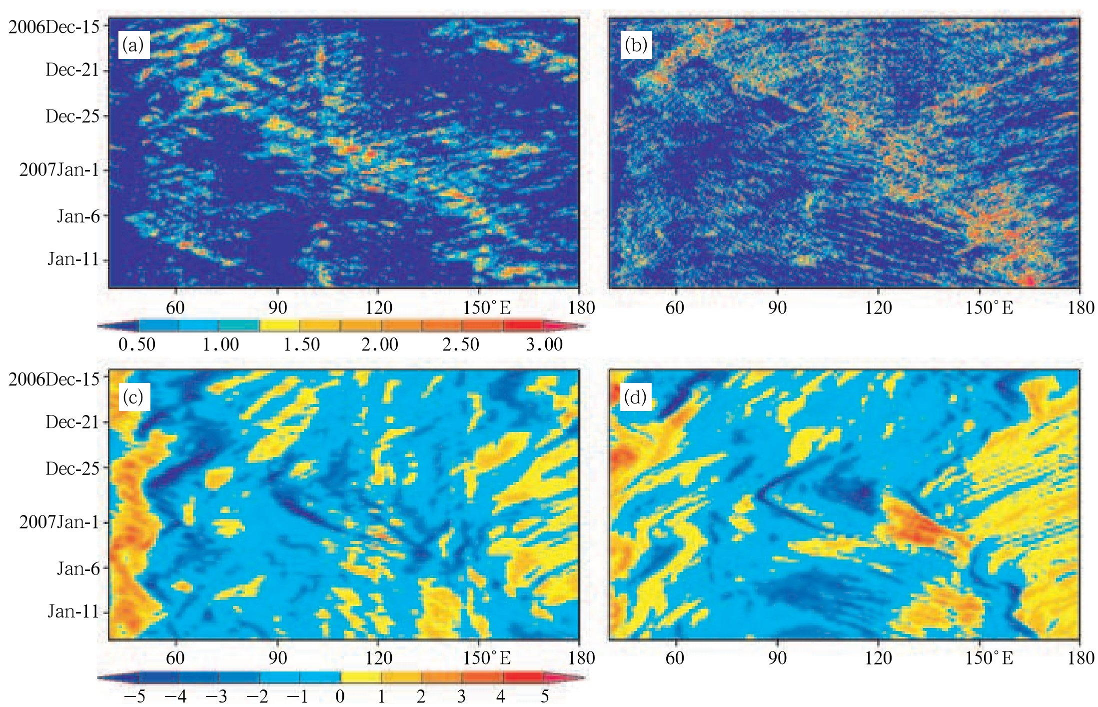

Fig.5. Time-longitude (Hovmöller) sections: precipitation (in mm h^{-1}) averaged between 10°S and 5°N from (a) the TRMM 3B42 data and (b) the 7-km grid run. The vorticity (10^{-5} s^{-1}) at the 850-hPa level averaged between 10° and 5°S from (c) the NCEP analyses and (d) the 7-km grid run. Adopted from Miura et al. (2007).

et al. (2007) successfully simulated the slow eastward migration of an MJO event during December 2006 to January 2007 (Fig.5). The results demonstrate the potential making of month-long MJO predictions when global cloud-resolving models with realistic initial conditions are used.

Very high-resolution models are necessary and critical for improved prediction of precipitation and statistical behavior of extreme events and high-impact weather. High resolution models may also be able to resolve the Meiyu front better. Synoptic disturbances play an important role in determination of extratropical monsoon climate variability. However, it remains to be demonstrated whether increased resolution and improved simulation of high-frequency perturbations would improve the slow coupled dynamics in the coupled climate models.

A key to improvement of intraseasonal prediction is to use coupled models and to better initialize the coupled system, because the intraseasonal prediction is sensitive to both atmospheric initial conditions (Waliser et al., 2003a; Reichler and Roads, 2005) and atmosphere-ocean interaction (Fu et al., 2007, 2008).

It should be addressed whether the MME approach could improve the skill of MJO/MISO prediction, although the MME has been proven to outperform a single model for the medium-range weather and hurricane forecasts (Krishnamurti et al., 1999, 2000). Application of MME to operational centers remains to be implemented. Building on experimental real-time efforts at CDC/NOAA (Waliser et al., 2006) and emerging operational efforts at CPC/NOAA and a number of other forecast centers, the US CLIVAR MJO Working Group has fostered the development of a multi-model operational MJO prediction framework. The most critical items needed to produce an MME forecast are: 1) an MJO-specific hindcast data set and 2) the development of an MME methodology relevant to the MJO.

Looking forward, the increase in the new observations and the advances in cloud resolving models, computer power, and communication technology are expected to provide breakthroughs in monsoon climate prediction.

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