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Asian Monsoon Years AMY2007-2012

The Science Plan for Asian Monsoon Years (AMY 2007-2012)

A cross-cutting WCRP initiative

WANG Bin, Jun MATSUMOTO, WU Guoxiong and LI Jianping

China Meteorological Press

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Summary

The Asian Monsoon Years (AMY 2007—2012) is a cross-cutting initiative as part of the International Monsoon Study (IMS), a coordinated observation and modeling effort under the leadership of the World Climate Research Programme (WCRP). The long-term goal of AMY is to improve Asian monsoon prediction for societal benefits through coordinated efforts to improve our understanding of Asian monsoon variability and predictability. It is believed that coordination and cooperation of individual participating and partner projects will greatly facilitate the efforts to reach this goal.

The specific objectives of AMY are:

• To better understand the ocean-atmosphere-land-biosphere interactions, the multi-scale interactions among time scales ranging from diurnal, intraseasonal to interannual, and the aerosol-cloud-water cycle interactions in the Asian monsoon system;

• To improve the physical representations of these interactions in coupled climate models, and to develop data assimilation of the ocean-atmosphere-land system in the Asian monsoon region.

• To determine predictability of the Asian monsoon on intraseasonal and seasonal time scales, and the roles of land initialization in continental seasonal rainfall prediction.

• To better understand how human activities in the Asian monsoon region interact with monsoon and its related environment.

These objectives will be fulfilled through coordination of the ongoing and planned field experiments and modeling projects in the Asian monsoon region which form contributions to AMY.

The AMY stems from grass-root scientific and societal imperatives. It has been endorsed by the Joint Scientific Committee (JSC) of WCRP as well as the WCRP Climate Variability and Predictability (CLIVAR) Project and the Global Energy and Water Cycle Experiment (GEWEX). It has been identified as a cross-cutting weather and climate activity by WMO World Weather Research Programme (WWRP) Monsoon Panel in the WWRP Strategic Plan. The AMY program is gaining increasing support within the broad community represented by many national projects, operational centers and monsoon research scientists at large.

The planned activity consists of field observations, data management, and modeling components. A Science Steering Committee, International Program Office, and three Working Groups have been set up as an outcome of the first AMY workshop at Beijing, April 23—25, 2007 hosted by State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP). A draft of this science plan was discussed at the Second AMY workshop jointly hosted by CLIVAR and GEWEX and BPPT, Indonesia at Bali, Indonesia, September 3—4, 2007. This final version also facilitated the working groups in formulating the Implementation plan.

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1 Introduction

About 60% of the world population inhabits the region of the Asian monsoon. Agriculture and, more widely, economy and society across Asia are critically influenced by the variability of the monsoon. Many of the Asian countries are developing countries whose economies are fast growing yet considerably affected by anomalous climate and disastrous weather events. Future change in the Asian monsoon climate is also of the greatest concern to the world economy and sustainable development.

The scientific importance of the Asian monsoon cannot be overemphasized. The giant Asian monsoon system dominates the entire Eastern Hemisphere tropics and subtropics. It interacts with the El Niño-Southern Oscillation (ENSO) and extratropical circulations, and has far-reaching impacts on global climate and environment. The Asian monsoon exemplifies the most complex interactions between the Earth's land surface, ocean, atmosphere, hydrosphere, cryosphere and biosphere including human activities.

Monsoon science has advanced enormously in the last two decades due to a wealth of new data from satellite observations and field experiments, and due to advances in computing power and mathematical representations of coupled climate systems. Driven by the needs to better understand and predict monsoons on all time scales from daily weather to climate change, monsoon research has received much attention in Asian monsoon regions. The Asian Monsoon Years (AMY 2007—2012) is a timely endeavor to integrate and coordinate these activities.

1.1 Programmatic development

Many major monsoon research activities and field projects are being planned in the time frame of 2008—2010 in China, Japan, India, Korea and many other countries. All funding supporting these projects comes from the individual nations. The Asian Monsoon Years 2007—2012 (AMY2007—2012) is based on these grass-root national efforts.

The concept of AMY was first proposed during the international workshop, "Impact of elevated aerosols on radiation-monsoon-water cycle interaction" in Xi'ning, China, in August, 2006. It was recognized that for a successful AMY, it is critical for an international body to provide science oversight, to facilitate promotion of collaboration and partnership among national programs, and to provide stewardship of the vast amount of data collected for the benefit of all interested parties.

The proposal soon gained strong support from the Climate Variability and Predictability (CLIVAR) Project and the Global Energy and Water Cycle Experiment (GEWEX) of WCRP (all acronyms in the text are listed in Appendix Ⅰ). The AMY concept stimulated continuing discussions at the GEWEX/Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHARSI) monsoon workshop, Tokyo, held from January 8—10 2007, the GEWEX SSG meeting, Honolulu, January 22—25 2007, and the CLIVAR/ Asian-Australian Monsoon Panel (AAMP) Meeting, Honolulu, February 19—22, 2007. On March 26—30 2007, the 28th Session of the WCRP Joint Scientific Committee (JSC) was held in Zanzibar, Tanzania. A document "MONSOON ACTIVITIES IN WCRP AND THE YEAR OF TROPICAL CONVECTION" (JSC-XXVIII/Doc. 2.3 (19.11. 2007)), was drafted for this meeting by J. Matsumoto, B. Wang, H. Cattle, R. Lawford, G. Wu, D. Walliser and T. Yasunari. Presentations to the JSC on monsoons were made by G. Wu (assisted by R. Lawford and H. Cattle), T. Yasunari and J. Shukla. The JSC subsequently endorsed the concept of the AMY as a contribution to an International Monsoon Study, a major initiative to promote broad-based climate research for the monsoon systems of the world. The AMY initiative was visualized as "a coordinated national and international observation and modeling activity to better understand the ocean-land-atmosphere interaction and the aerosol-cloud-radiation-monsoon interaction of the Asian monsoon system, for improving monsoon prediction".

A series of conferences/workshops have been organized to coordinate ongoing activities and to plan the AMY after the WCRP JSC meeting. China hosted the first International Workshop on AMY in Beijing, April 23—25 2007. Informal discussions continued in the Monsoon system session of the XXIV General Assembly of International Union of Geodesy and Geophysics (IUGG) in Perugia, Italy July 2—13 2007, the International Symposium, "Celebrating the monsoon", July 24—28 2007 held at Bangalore, India, and at the fourth meeting of the Asia Oceania Geosciences Society (AOGS), Thailand July 30-August 4 2007. The Second AMY workshop jointly hosted by CLIVAR and GEWEX, and BPPT, Indonesia was held at Bali, Indonesia on September 3—4, 2007. The draft science plan was discussed in the workshop. Based on the discussion, the draft version has been revised.

1.2 Participants

AMY integrates existing national and international research programs in the Asian monsoon regions. Currently, AMY has involved 24 national, regional and multi-national projects and a total of 24 participating organizations (Appendix Ⅱ). These include the following national and regional projects:

- Japan-JEPP (Tibet, SEA, Thailand, IO, Maritime Continent: HARIMAU), JAMSTEC/IORGC, JAMSTEC/FRCGC, CREST-SEA, ARCS-Asia, PRAISE;
- China-AIPO, SCHeREX, TORP, SACOL, NPOIMS;
- India-STORM, CTCZ, IITM/Rain, CAIPEEX;
- Korea-Japan: PHONE08;
- USA-JAMEX, SMART-COMMIT, TIGERZ;
- Chinese Taipei-SoWMEX, TiMREX, EAMEX;
- China-Japan JICA/Tibet Project;
- CEOP/WEBS.

The approximate regional extent of these projects is shown in Fig. 1.

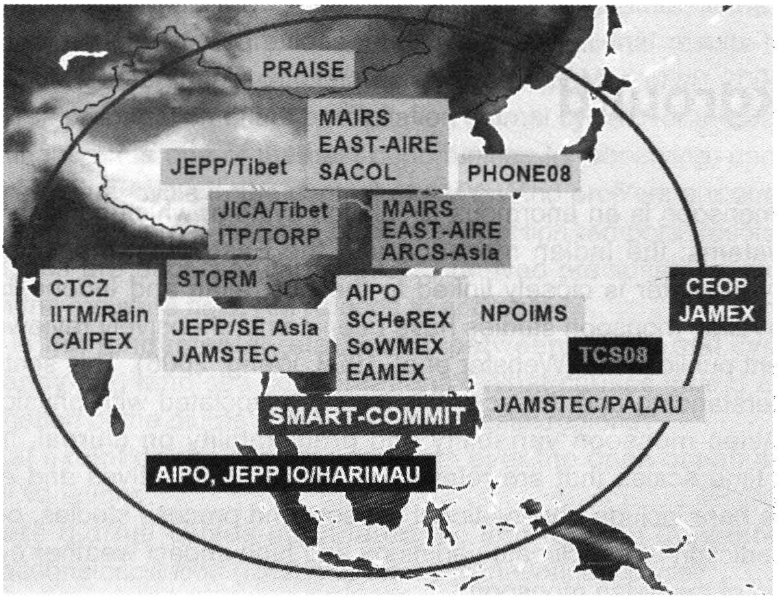

Fig. 1 Participating national/regional projects contributing to AMY.

In addition, the following international projects and the activities of the APEC Climate Center (APCC) provide a wider geographical and international perspective:

- GEWEX-CEOP, MAHASRI, GaME-T;
- CLIVAR-AMMP, IOP, POP;
- ESSP-MAIRS;
- WWRP-TMR-TCS08.

2 Background

The Asian monsoon is an enormous circulation system, which consists of two major monsoon subsystems: the Indian monsoon and the East Asian monsoon. Prominent monsoon activity in winter is closely linked to the Australian and Indonesian monsoon. The advances in Asian monsoon studies have been comprehensively reviewed by leading scientists in recent publications (Webster *et al.* 1998, Wang, 2006). This section describes the present understanding and the scientific issues associated with physical processes governing the Asian monsoon variability and predictability on diurnal, intraseasonal and interannual time scales that are relevant to the AMY objectives and activities. Our primary concerns here include observational aspects and process studies, our capacity in modeling and prediction of the climate variations and high impact weather events, as well as future changes of the Asian monsoon.

2.1 Observational and process studies

a. Diurnal cycle

The diurnal cycle is one of the most fundamental atmospheric responses to the solar radiation forcing; it also plays an important role in regulating monsoon rainfall and circulation. Diurnal cycles driven by solar forcing provide an efficient way for verification of physical parameterizations in models, including those for surface fluxes and the planetary boundary layer and cloud (Yang and Slingo, 2001). The diurnal cycle is most relevant for revealing monsoon modelling problems because the largest precipitation diurnal cycles are associated with monsoons and because the most complex behaviors associated with the diurnal cycle are located in the monsoon regions (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 including monsoon Asia. After the launch of the geo-stationary satellites, minute diurnal features of convective activities have been revealed by using infrared radiation data (Murakami, 1983; Nitta and Sekine, 1994). Comparisons of satellite and gauge data have been conducted in Indochina in the GAME project (Ohsawa *et al.*, 2001). Recently, accumulation of the Tropical Rainfall Measuring Mission (TRMM) satellite observations has enabled us to capture the minute features of diurnal variations in the entire tropics (e.g., Sorooshan *et al.*, 2002; Nesbitt and Zipser, 2003; Kikuchi and Wang, 2008). Observation by surface radar also provides a detailed view of the fast moving cloud and rainfall systems (Okumura *et al.*, 2003). Some of these features have been reproduced in regional model simulations (Satomura, 2000).

However, the description of the diurnal cycle using satellite data is, in many cases, only for clouds and rainfall; the related circulation and/or other fields have not been fully analyzed, although a few previous intensive observational results have provided a comprehensive view of regional scale characteristics (e.g., Mori *et al.*, 2004; Sakurai *et al.*, 2005). The phase propagation of the precipitation diurnal cycle over the Bay of Bengal and Maritime Continent offers one of the best opportunities for observing, understanding, and modeling of the diurnal cycle in the context of AMY. Wind profilers are one of the possible tools for detecting the diurnal features of circulation. High temporal resolution upper-level wind observations are necessary. In situ GPS derived precipitable water can also add information on the moisture field. AMY needs to address:

- What is the fundamental relationship between the diurnal cycle and surface orography and land/sea configurations? What causes inland and ocean-ward propagation of the diurnal cycle from the coastal regions?
- To what extent do the diurnal variations over the open ocean affect the cloud/rainfall variations?
- How are diurnal cycles modulated by, and how do they interact with, the intraseasonaloscillation (ISO) and the seasonal/annual cycle?

b. Annual cycle

The monsoon is a manifestation of the annual cycle (Webster *et al.* 1998, Zeng and Li, 2002; Goswami *et al.* 2006, Wang and Ding, 2008), so the understanding of the basic characteristics and mechanisms of the annual cycle is fundamental to many topics in the study of monsoon. Beyond scientific importance, the onset and withdrawal of the monsoons is of vital importance to the larger community, because agriculture and other human activities are strongly influenced by the spatial and time distribution of the monsoon rainy season. Although solar radiation forcing is sinusoidal in nature, the seasonal cycle of the Asian monsoon system is more complex and includes both relatively smooth and abrupt changes (e.g., Tao and Chen, 1987; Ninomiya and Murakami, 1987; Matsumoto, 1992, 1997; Ding, 1994, 2004; Wang and LinHo, 2002; Ueda and Yasunari, 1996; Minoura *et al.*, 2003; Ueda, 2005; Chang *et al.*, 2005a, b).

Many studies have identified two stages of the onset of the Asian monsoon. The first stage starts from the Andaman Sea in the end of April and then rapidly extends northeastward toward Indo-China in early May, and to the South China Sea (SCS) and Okinawa in mid May to establish the early season rain band (e.g., Tao and Chen, 1987; Wang and LinHo 2002; Ding 2004, 2007). This elongated rain band is planetary scale in length and in the mature stage can extend from the Arabian Sea to the northwestern Pacific Ocean (e.g., Chen and Chang, 1980; Kiguchi and Matsumoto, 2005). The convective rainfall produces upper tropospheric heating in its vicinity (Ishizaki and Ueda, 2005; Kodama *et al.*, 2005) as well as over the Tibetan Plateau (Ueda *et al.*, 2003; Taniguchi and Koike, 2007).

A critical question is: What are the processes that produce this drastic onset in late spring? Since both internal dynamics and lower boundary forcing likely play important roles, a second question that has large ramifications for society is, to what extent the onset in each of the different parts of the Asian monsoon domain is predictable? Influence of slowly varying lower boundary forcing (e.g. ENSO) on the Indian monsoon onset over Kerala arises through modulation of meridional gradient of the tropospheric temperature over the region (Goswami and Xavier, 2005, Xavier *et al.*, 2007). The onset over the northern SCS is often associated with southward-propagating fronts from mainland China (Chang and Chen, 1995), making the onset in eastern China distinct from India where northerly disturbances are blocked by the Tibetan Plateau. In many instances, onset over the SCS is connected with the development of a low-level vortex over the Bay of Bengal, often associated with the passage of the Madden-Julian Oscillation (MJO) in the Indian Ocean, and this vortex serves to transport moisture across Indo-China to the SCS (Ding and Liu, 2001). The monsoon onset over India is frequently accompanied by an onset vortex over the Arabian Sea. A third question is, are these synoptic and intraseasonal motions a response of the broad scale regime changes or do they interact with the basic state to play a critical role in the onset?

The second stage of monsoon onset is usually characterized by the synchronized initiation of the Indian rainy season and the Meiyu/Baiu in early to mid-June. In addition to the two stages of the onsets the Asian monsoon undergoes prominent intraseasonal oscillations (ISOs), Periods of active rainfall over India followed by breaks on a 10—20 day time scale are routinely observed during the summer monsoon. This active-break cycle has been attributed by Sikka and Gagdil (1980) and others to northward-propagating intraseasonal oscillations (ISOs); to disturbances moving westward from the SCS with a 10—20 day period by Krishnamurti and Bhalme (1976); to bifurcating cyclonic vortices representing trailing Rossby waves behind a rapidly propagating Kelvin wave (Lawrence and Webster, 2001); to processes within the monsoon region itself that cause it to be a self-regulating, coupled system (Wang *et al.*, 2004); and to an interaction between deep convection and the deep-tropospheric, zonally sheared, monsoon flow (Wang, 2005). A distinctive feature is that a significant part of the oscillations is calendar locked. This climatological intraseasonal oscillation (CISO) or sudden changes within the seasonal march (Wang and Xu, 1997) reflects a monsoon singularity and its mechanism is another major question that should be addressed.

On the broader scale the seasonal march of the Asian-Australian monsoon can be described by the evolution of the regional rainfall regimes. The central and pivotal area where the different regimes intersect and interact directly is situated between the tropical western Pacific and the tropical eastern Indian Ocean, where the complex land-sea distribution encompasses the Bay of Bengal, the Indo-China Peninsula, the SCS, the Philippines, and the Maritime Continent and adjacent land and sea areas. This is a region with abundant heat sources where local development often closely interacts with the annual cycle of the entire Asian monsoon domain. In general the Bay of Bengal, Indo-China Peninsula and Philippines are in the Asian summer monsoon regime while the Maritime Continent experiences a wet monsoon during boreal winter and a dry season during boreal summer. Newly available satellite observations together with long-term historical station rainfall data reveal a complex structure of the monsoon regimes of all four seasons (Chang *et al.*, 2005a, 2006). The annual cycle is dominated largely by interactions between the complex terrain and a simple annual reversal of the surface monsoonal winds throughout all monsoon regions from the Indian Ocean to the SCS and the equatorial western Pacific. The semiannual cycle is comparable in magnitude to the annual cycle over parts of the equatorial landmasses, but only a very small region reflects the twice-yearly crossing of the sun. Most of the semiannual cycle is due to the influence of both the summer and the winter monsoon in the western part of the Maritime Continent. Analysis of TRMM data reveals a structure whereby the boreal summer and winter monsoon rainfall regimes intertwine across the equator and both are strongly affected by local wind-terrain interactions. In particular the boreal winter regime extends far northward along the eastern flanks of the major island groups and landmasses.

In the transitional seasons the seasonal march is not symmetric. In fall, the maximum convection follows a gradual southeastward progression path in the transition from the Asian summer monsoon to the Asian winter monsoon. However in spring the transition from winter to summer monsoon is sudden. This asymmetric feature has long been recognized through its manifestation in the positions of the ITCZ (Meehl, 1987; Matsumoto and Murakami, 2002). A fundamental question is, what are the processes leading to this spring-fall asymmetry? Are they the result of asymmetric global-scale atmosphere-ocean interaction (Webster *et al.*, 1998), wave responses to tropical heat source forcing (Hung *et al.*, 2004), or the redistribution of mass between land and ocean areas during spring and fall that results from different land-ocean thermal memories (Chang *et al.*, 2005a; Wang and Chang, 2008)? Since the sudden spring transition makes seasonal prediction of the Asian summer monsoon difficult, this question is closely related to that of the abrupt monsoon onset and may also be related to the "spring prediction barrier" problem.

c. Extreme and high-impact weather

Severe local thunderstorms, rain and snow storms are major hazardous extreme weather events that have high socio-economic significance. Improvement in understanding the occurrence, processes and mechanisms of these severe stormy weathers is of immense scientific importance for the better prediction of high-impact weather events and needs to be addressed.

For the Asian winter monsoon, the interactions between the cold surge from Siberia, local synoptic circulation and intraseasonal variability (mainly the MJO) often produce snow storms and high winds in East Asia as well as heavy rainfall over Southeast Asia and the Maritime Continent (Chang *et al*, 2005b, 2006). The outbreaks of two severe cold waves in the 2004/2005 winter and the prolonged snowfall and freezing rain event in the Huai-Yangtze river basin in January of 2008 are most remarkable extreme and high-impact weather in East Asia in recent winter years. In Southeast Asia, interactions with the diurnally varying local circulation were important for the continuous torrential rains that occurred in Jakarta in early February, 2007 (Wu *et al.*, 2007). In addition, interaction between cold surges and tropical circulations including MJO and tropical cyclone activity may be the key features of severe rainfalls in the central coastal area of Vietnam (Yokoi and Matsumoto, 2008). An extreme typhoon case occurred in December 2001 when Typhoon Vamei formed in the equatorial South China Sea as a result of interactions between a cold surge and a terrain induced stationary equatorial vortex (Chang *et al.*, 2003; Chambers and Li, 2007).

For the East Asian summer monsoon in which heavy rainfall is often dominated by the Meiyu-Baiu-Changma system, southwesterly monsoon surges that occur during monsoon onset and active periods, and after the passage of topical cyclones, also led to torrential rainfall around the northern South China Sea, East China Sea, southern China and the Yangtze River basin (e.g., Jou and Deng, 1998; Chen *et al.*, 2003; Chen, 2004; Ding and Chan, 2005; Johnson *et al.*, 2004; Johnson, 2006; Lee *et al.*, 2006). Interactions between larger scale mid-latitude disturbances and upper tropospheric potential vorticity as well as with diurnal convection and vorticity generation mechanisms in the Tibetan Plateau region often play critical roles in causing severe rainfall events in the Yangze River Valley. Examples include the notable summer monsoon rainfall events in 1992 (Chang *et al.*, 1998, 2000b) and 1998 (Yasunari and Miwa, 2006). The cross-equatorial propagation of the preceding strong Southern Hemisphere annular mode (SAM) signal from the Southern Hemisphere to the Northern Hemisphere, associated with the anomalous subseasonal oscillation of the western Pacific subtropical high (WPSH), has also been suggested as a possible factor contributing to the strong summer coexistence of droughts/floods during the summer monsoon season in the Yangtze River Valley (Wu *et al.*, 2006a, b). For the South Asian summer monsoon, major heavy rainfalls and monsoon depression and storms occur in the period of the active monsoon, which often bring about devastating floods in the central and northern India and Bangladesh (Ding and Sikka, 2006).

At sub-seasonal time scales, synoptic systems such as monsoon depressions having a horizontal scale of about 2000—3000 km form over the quasi-stationary seasonal monsoon trough. They are, by far, the most important components of the monsoon circulation. During the peak monsoon season (July-August), a majority of them form over the warm waters of northern Bay of Bengal, and move in a west-northwesterly direction with an average phase speed of about 3 $m \cdot s^{-1}$ On average 4—6 systems form each year. Their observational characteristics are well documented and readers are referred to Sikka (2006). In most places over central India, the rainfall associated with monsoon depressions contributes to about 50% of the seasonal mean, with almost all extreme rainfall events there attested to them (Sikka, 2000). A careful analysis of observed daily rainfall along the monsoon trough reveals an increase in the incidence of intense rainfall events in recent decades (Goswami *et al.*, 2006).

d. Monsoon Intraseasonal Oscillation (MISO)

The MISO is a dominant mode of subseasonal variability that links weather and climate. MISO is closely related to the onset, active and break periods of the monsoons. The behavior of MISO is linked to the equatorial eastward propagating MJO but more complex than MJO due to interactions between monsoon flows and the MJO. The monsoon circulation can fundamentally modify MJO during boreal summer. In addition, the monsoon has its own intraseasonal variability (ISV) modes,for instance, the bi-weekly mode (Murakami, 1975; Krishnamurti and Bhalme, 1976; Chatterjee and Goswami, 2004) and independent northward propagating 30 day mode (Wang and Rui, 1990a, b; Hendon *et al.*, 2007).

It has been generally recognized that the MISO has the following distinctive and essential features (Goswami 2005; Waliser *et al.*, 2006): (a) northward propagation in the Indian monsoon region (Yasunari, 1979, 1980; Sikka and Gadgel, 1980) and northwestward propagation in the western North Pacific (e.g., Lau and Chan, 1986; Nitta, 1987; Hsu and Weng, 2001); (b) formation of an NW-SE tilted anomalous rain band near Sumatra (Maloney and Hartmann, 1998; Annamalai and Slingo, 2001; Kemball-Cook and Wang, 2001; Lawrence and Webster, 2002; Waliser *et al.*, 2003a, b); (c) initiation in the western Equatorial Indian Ocean (EIO 60°—70°E) (Wang *et al.*, 2005, 2006b; Jiang and Li, 2005), (d) phase-lock to the monsoon annual cycle, or climatological ISO (CISO) (Nakazawa, 1992; Wang and Xu, 1997; LinHo and Wang, 2002), and (e) a prominent 10—25 day oscillation in the off-equatorial South Asian monsoon trough (Murakami, 1975; Krishnamurti and Bhalme, 1976; Chen and Chen, 1993; Wu and Zhang, 1998; Chatterjee and Goswami, 2004; Kikuchi and Wang, 2008; Wen and Zhang, 2007, 2008; Krishnamurthi and Shukla, 2008) and 10-20 day ISVs in the upper tropospheric water vapor (UTWV) over both South Asia and East Asia (Zhan *et al.*, 2006). In addition, MISO has close interaction with ISVs in the mid-latitude region (Iwasaki and Nii, 2006; 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, 2004). The westward propagating 10—20 day ISV seems to owe its origin to a convectively unstable gravest meridional mode equatorial Rossby wave in the presence of the mean monsoon flows (Chatterjee and Goswami, 2004). The formation of the NW-SE tilted precipitation belt has been interpreted as a bifurcation of the MJO in decaying equatorial MJO disturbances and emanation of convectively coupled equatorial Rossby waves (Wang and Xu, 1997; Lawrence and Webster, 2002; Annamalai and Sperber 2005). The re-initiation of the monsoon active-break cycles has been attributed to local SST and hydrological feedback (Stephens *et al.*, 2004) and a self-induction mechanism (Wang *et al.*, 2005, 2006b). The role of the topographic effect of the maritime continent has also been discussed (Hsu *et al.*, 2004; Hsu and Lee, 2005).

However, full interpretation of the MISO phenomena remains elusive. MISO involves multi-scale interactions among diurnal, meso-, synoptic, MJO, and monsoon annual cycle scales. AMY should consider what the priority is for future field and modeling studies and for improving observing and modeling strategies. In this regard, the following issues require investigation:

What are the major modes of the MISO? Are there any fundamental differences between MISO and the MJO?

- What is the typical multi-scale structure of MJO and MISO?
- How are organized convection systems linked to large scale forcing? What are triggers for organized convective events in general?
- Are multi-scale interactions essential for development and maintenance MJO and MISO and if so how?
- How do we get a complete theoretical framework for describing the characteristics of MJO?
- How is MJO in the Indian Ocean affected by the dynamic and thermodynamic effects of the islands in the Indonesian Maritime Continent?
- Why is there a 10—20 day oscillation and how is it related to MISO?

It is suggested that AMY should promote integrated usage of satellite observations to conduct comprehensive studies of the 3-D structure and evolution of MJO. AMY field campaigns should aim at observing the organization of convection and multi-scale structure of the MJO over the equatorial Indian Ocean, Maritime Continent, and along the tropical monsoon trough.

e. Interannual variability

A great portion of the monsoon literature has documented the year-to-year variability in various monsoon regions, including the Indian monsoon (e.g., Mooley and Parthasarathy, 1984; Shukla and Mooley, 1987), the Indonesian-Australian 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, 2002, 2003, 2005; Zhou and Yu, 2005), and the western North Pacific monsoon (Wu and Wang, 2000). The rainfall and circulation anomalies in many of the aforementioned regions exhibit a major two-to-three-year spectral peak (e.g., Meehl, 1987; Lau and Shen, 1988; Ropelewski *et al.*, 1992; Chen and Yoon, 2000; Meehl and Ablaster, 2002). This is often referred to as the Tropospheric Biennial Oscillation (TBO) (Meehl, 1993; Miyakoda *et al.*, 1999). Comprehensive reviews have been recently provided by Webster (2006) and Yang and Lau (2006).

The Asian-Australian monsoon (A-AM) region, spanning from about 40°E to 160°E and from 30°S to 40°N, covers one-third of the global tropics and subtropics. The entire Indo-Pacific warm pool is under the influence of the A-AM. Efforts have been made toward understanding the A-AM's broad-scale interannual variability (e.g., Meehl, 1987; Webster and Yang, 1992; Goswami *et al.* 1999; Navarra *et al.*, 1999; Kim and Lau, 2001; Wang *et al.*, 2003; Lau and Wang, 2005; Li *et al.*, 2006). These studies have paid specific attention to the relationship between El Niño-Southern Oscillation (ENSO) and the monsoon. An integral view of the year-to-year variability of the entire A-AM system has been developed. Two major modes of variability for the period 1956—2004 have been identified (Wang *et al.*, 2007). 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 Tropical Biennial Oscillation (TBO). The second mode leads ENSO by one year and is driven by SST anomalies associated with La Niña (Zhou *et al.*, 2007).

The remote forcing from the eastern Pacific through atmospheric teleconnection is no doubt a chief factor in Asian monsoon variations. But this is not the full story. Slingo and Annamalai (2000) suggested the active role of ENSO-induced regional SST anomalies in overshadowing the suppressing effect of ENSO on the monsoon. Recently, Gadgil *et al.* (2004) has shown that Indian monsoon rainfall variability is determined by both ENSO and equatorial Indian Ocean variability. These works reconfirm the Charney-Shukla (1981) hypothesis regarding the effect of boundary conditions on climate predictability (Shukla, 1998). A simple conceptual model that was presented by Krishnamurthy and Shukla (2000) suggests that the observed seasonal rainfall is a nearly linear combination of boundary forced larger scale seasonal mean and regional anomalies associated with intraseasonal variations.

The monsoon-warm pool ocean interaction can generate SST anomalies in the Indian Ocean. The Indian-Ocean dipole (IOD) or zonal mode is a beautiful example (Saji *et al.*, 1999; Webster *et al.*, 1999). The IOD has profound impacts on monsoon rainfall anomalies in the Indian Ocean and over India and South Asia, East Africa, Maritime Continent, East Asia, and the western North Pacific (Guan and Yamagata, 2003). The processes supporting IOD have been attributed to equatorial Bjerkness positive feedback (IOD/IOZM) (Webster *et al.*, 1999; Saji *et al.*, 1999) and the off-equatorial convectively coupled Rossby wave-SST feedback (Wang *et al.*, 2000, 2003). The Rossby wave-SST dipole feedback can be either positive or negative depending on background flows (the monsoon annual cycle). The monsoon basic flow can not only regulate the nature of the atmosphere-ocean interaction (Nichols, 1983) but also significantly modify the monsoon response to remote ENSO forcing and cause seasonal march of interannual anomalies (Meehl, 1987). Thus, the remote El Niño forcing, the monsoon-warm pool ocean interaction, and the influence of the annual cycle are three fundamental factors for understanding the behavior of the leading mode (Wang *et al.*, 2003).

Monsoon-ocean interaction can also provide an important negative feedback by monsoon-induced anomalies in the surface heat fluxes (Lau and Nath, 2000) or 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). Another process that contributing to the TBO is in the memories of ocean mixed layer changes land-sea contrast (Meehl, 1994, 1997).

The effects of the soil moisture and snow cover have long been recognized as a source of Asian monsoon variability, especially for the rainfall over continental monsoon regions (Bamzai and Shukla, 1999; Zhang *et al.*, 2004). Yasunari (1991) and Dirmeyer *et al.* (1999) found that the land surface conditions in spring have an impact on the following summer monsoon. Shen *et al.* (1998) investigated the impact of Eurasian snowfall and concluded that it plays a part but does not overwhelm the SST-impacts. Further, observational studies on the seasonal march of the temperature and circulation fields over Eurasia from spring to summer have shown that the influence of snow cover and related soil moisture anomaly on the temperature and circulation anomalies in the lower troposphere is limited primarily to when and where snow cover exists seasonally (Shinoda *et al.*, 2001; Robock *et al.*, 2003). Therefore, more studies are needed to understand how snow in the Eurasian Continent and/or over the Tibetan Plateau can affect succeeding monsoon activity.

On the interannual scale, there are strong signals of links of the variation of the continental tropical convergence zone (TCZ) with convection over the equatorial Indian Ocean, in addition to the well known link with ENSO (Gadgil *et al.*, 2004). Understanding the mechanisms responsible for the variation of convection over the critical regions of the equatorial Indian Ocean, therefore, assumes enormous importance for our understanding the variations of the continental TCZ on both the intraseasonal and interannual scales.

f. Interdecadal variability and trends

Significant interdecadal variations in summer monsoon rainfall have been known from study of long instrumental records, for instance, the all Indian summer monsoon rainfall (1871-present) and the rainfall in Seoul (1778-present) (Kripalani and Kulkarni, 1997; Goswami 2006; Wang *et al.*, 2006a). An extratropical teleconnection mechanism has been proposed (Goswami *et al.* 2006) for observed strong linkages between multidecadal variability of Indian monsoon and the Atlantic Multidecadal Oscillation (AMO). In the past 50—60 years, there have been clear signals in rainfall pattern changes in the East Asian summer monsoon (Nitta and Hu, 1996; Chang *et al.*, 2000a; Yu *et al.*, 2004; Li and Zeng, 2005) around the late 1970s. It is, however, not clear just what the coherent structure of this interdecadal change is and how this rapid change occurred. Uncertainty in the reanalysis datasets (Kinter *et al.*, 2002) is one of the major road blocks for determining the processes determining the interdecadal variations.

The Indian monsoon-ENSO relationship is non-stationary, so is the ENSO property. The anticorrelation between Indian summer monsoon and ENSO has been weakening since the late 1970s (Shukla, 1995; Webster *et al.*, 1998; Kumar *et al.*, 1999; Krishnamurthy and Goswami 2000; Chang *et al.*, 2001). However, the relationships between ENSO and the western North Pacific, East Asian, and Indonesian monsoons have all become enhanced during ENSO's developing, mature and decaying phases since the late 1970s (Wang *et al.*, 2007). The latter appears to override the weakening of the Indian monsoon-ENSO relationship so that the overall coupling between the A-AM system and ENSO has become strengthened. These interdecadal changes have been attributed to changes in ENSO properties as previously documented (Wang, 1995; Gu and Philander, 1996; An and Wang, 2000). The increased magnitude and periodicity of ENSO since the late 1970s and the associated strengthened monsoon-ocean interaction may be responsible for the changes in monsoon-ENSO relationship. On the other hand, Kawamura *et al.* (2005) has noted that although the relationship between the all-India monsoon rainfall index and ENSO has weakened after the late 1970s, when viewed regionally the relationship is still robust between the rainfall in northeast India and ENSO. Such regional features in the whole A-A monsoon domain have not been fully revealed yet and should be examined. Annamalai *et al.* (2007) examined the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models and noted