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CONTENTS

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Advances of the Studies on the East Asian Summer Monsoon and Problems to Be Studied Further

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Advances of the recent studies on the features of construction, interannual and intraseasonal variations of the East Asian summer monsoon and their causes are reviewed. Moreover, results of the most new studies on simulation and predictability of the East Asian summer monsoon are also reviewed; particularly, the difference of the characteristis between the East Asian summer monsoon and the Indian summer monsoon, and the effect of ENSO cycle, the western Pacific warm pool and the Tibetan Plateau on the interannual and intraseasonal variations of the East Asian summer monsoon are systematically reviewed. Besides, the problems needed to be studied further on the variability of East Asian summer monsoon and its simulation and prediction are put forward.

Key words: East Asian monsoon; interannual variation; intraseasonal variation; ENSO cycle.

1. INTRODUCTION

Monsoon is a kind of climatic phenomenon, in which dominant wind system changes with seasons. Many studies (Tao and Chen, 1985; Ding, 1994; Yasunari and Seki, 1992) showed that Asian monsoon and Australian monsoon play an important role in the global climate variability. The monsoons can bring a large amount of water vapour from the Pacific Ocean and the Indian Ocean to the mainland. As a consequence, a large amount of rainfall can be formed in the monsoon regions. Because of the close relationship between monsoon and rainfall, monsoon influences economy, industry, agriculture and daily life of people in the monsoon regions, especially drought and flood caused by monsoon may bring heavy economical losses in these regions.

South Asia and East Asia are in a huge monsoon system, of which the East Asian monsoon is a submonsoon system. In East Asia there are many characteristic weather systems in different seasons, such as the Meiyu in China, the Changma in Korea and the Baiu in Japan in summer, persisting northwest winds and cold surges in winter. The interannual and intraseasonal variabilities of the East Asian monsoon are very large and can cause drought and flood in the eastern part of China, Korea and Japan. Therefore, the study on the East

Asian monsoon has become one of the important scientific issues in China, Korea and Japan for more than sixty years ago. Zhu (1934) first proposed the possible relationship between the East Asian summer monsoon and rainfall in China. Later, Tu and Huang (1944) investigated the advance and retreat of the summer monsoon in East Asia. These studies opened the way to search into the regularity of the East Asian monsoon variability and its impact on the climate in East Asia.

About the studies on the East Asian summer monsoon, Tao and Chen (1987) have made a systematical review. After their review, the studies on the structure, the interannual and intraseasonal variations and their cause, simulation and predication of the East Asian summer monsoon, especially the physical mechanism of interannual and intraseasonal variabilites, the water vapour transported by the Asian summer monsoon flow and the water vapour and energy cycles in the monsoon region have been greatly advanced.

In order to summarize these advances, which made a deeper study of the East Asian monsoon, the advances of the recent studies on the East Asian summer monsoon are reviewed, and the problems, which need to be studied further, are pointed out in this paper.

2. MEAN STRUCTURE OF THE EAST ASIAN SUMMER MONSOON SYSTEM AND ITS DIFFERENCES FROM THE INDIAN MONSOON SYSTEM

The South Asian monsoon and the East Asian monsoon form the strongest monsoon systems in the world. Thus, many scholars considered them as one monsoon system. However, there are some differences between these two monsoon systems. Many investigations showed that the East Asian summer monsoon has not only the part of the tropical monsoon, but also the part of the subtropical monsoon. But the Indian monsoon is only the tropical monsoon. Therefore, mean structure of the East Asian summer monsoon is different from the Indian monsoon in many aspects.

2.1 *Components of the East Asian Summer Monsoon and Its Differences from the Indian Monsoon System*

According to Krishnamurti's (1982) study, the principal components of the Indian monsoon include: the Mascarene high, the Somali cross–equatorial low–level flow and the monsoon trough over north India in the lower troposphere, and the South Asian high and the cross–equatorial flow, which flows from north to south, in the upper troposphere. However, Tao's investigation (Tao and Chen, 1985) showed that, as shown in Figure 1, the components of the East Asian summer monsoon include: (1) the Indian SW monsoon flow; (2) the Australian cold anticyclone; (3) the cross–equatorial flow along the east to 100°E; (4) the monsoon trough (or ITCZ) over the South China Sea and the tropical western Pacific; (5) the western Pacific subtropical high and the tropical easterly flow; (6) the Meiyu (or Baiu in Japan or Changma in Korea) frontal zones; (7) the disturbances in the mid–latitudes; Therefore, the East Asian summer monsoon is a circulation system, which is relatively independent of the Indian monsoon system, and it is influenced not only by the SW monsoon flow, but also by the subtropical high and the disturbances in the mid–latitudes.The investigation (see, Tao and Zhu et al., 1993) showed that the northward or southward shift of the components of the East Asian monsoon system may cause the drought and flood disasters in the Yangtze River and the Huaihe River valley of China, the Korean Peninsula and Japan.

2.2 *The Mean Meridional Circulation of the East Asian Summer Monsoon*

Because the Tibetan Plateau is in the north of the Indian monsoon region and the west of the East Asian monsoon region, the mean meridional circulation from the East Asian monsoon region to Australia is different from that in the Indian monsoon region. In the early–summer, the air flow can penetrate from the mid–latitudes to South China in the East Asian monsoon region. As shown in Tao and Chen (1987), the monsoon trough (ITCZ) is located at 15°E, where the strong convective activities are very vigorous and an ascent motion resulting from the very intense convective activities prevails. Moreover, the equatorward and northward meridional flows are in the upper troposphere over the monsoon trough due to the divergence of the flow. Due to the effect of Coriolis force, the equatorward branch contributes to the formation of the easterly jet stream between 5°N and 10°N. Besides, the strong convective activities are in the Meiyu front in China, the Baiu front in Japan and Changma front in Korea, and another ascent motion resulting from the strong convective activities prevails in the Meiyu front. As the same as the metioned above case, due to the ascent motion, the southward and northward meridional flows can be formed in the upper troposphere over the East Asian monsoon, respectively. Because the northward flow from the area over the ITCZ converges with the southward flow from the area over the Meiyu front, a descent motion can be formed over the area near 25°N. The descent motion also contributes to the formation of the subtropical high.

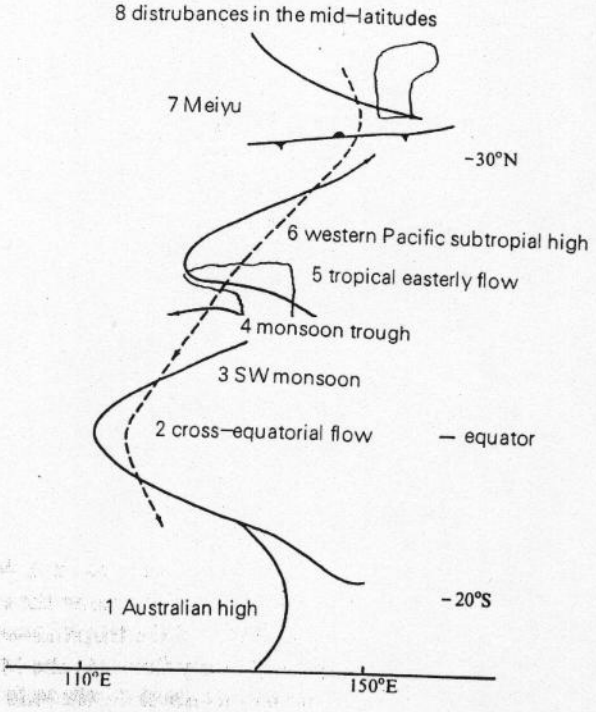

FIGURE 1. Distribution of the components of the East Asian monsoon system (after Tao and Chen, 1985).

According to Wang and Tao's (1984) investigation, the meridional circulation in the summer with the strong East Asian summer monsoon is different from that in the summer with the weak monsoon. When the East Asian summer monsoon is strong, the meridional circulation is also intensified. On the contrary, when the East Asian summer monsoon is weak, the meridional circulation is also weakened.

2.3 *The Characteristics of Water Vapour Transport in the East Asian Monsoon Region and Its Difference from That in the Indian Monsoon Region in Summer*

According to the result studied by Huang et al. (1998), the characteristics of water vapour transport in the East Asian monsoon region is greatly different from that in the Indian monsoon region in summer. The distribution of water vapour is uniform, and its gradients in the zonal and meridional directions are smaller in the Indian monsoon region. However, the distribution of water vapour is very un–uniform, and its gradient in the meridional direction is very large in the East Asian monsoon region. Therefore, in summer, the convergence or divergence of water vapour is mainly caused by the moisture advection in the East Asian monsoon, but it is mainly caused by the convergence or divergence of wind field in the Indian monsoon region. Moreover, in summer, the zonal transport is dominant, while the meridional transport is very small in the water vapour transport in the Indian monsoon region. However, the meridional transport is very large in the water vapour transport in the East Asian monsoon region.

2.4 *Characteristics of the Meiyu Front*

Several previous studies on the Meiyu front in China or the Baiu front in Japan (Ninomiya, 1984, 1985) have shown that the Meiyu front is a quasi–standing front, in which there are intense convective activities and rainfall systems, and it is associated with the low–level jet stream and strong moisture gradient in the lower troposphere over East Asia. The Meiyu front includes planetary and synoptic–scale frontal systems and meso–scale cloud system (Ninomiya and Akiyama, 1992). During the Meiyu season, heavy rainfall is closely associated with these meso–scale disturbances either in China or in Korea and Japan.

In East Asia, the summer rainfall phenomena are closely associated with the Meiyu front. Moreover, the formation and maintenance of the Meiyu front are greatly influenced not only by the southwesterly flow from the Indian Ocean and the southeasterly flow around the subtropical high over the western Pacific, but also by the mid–latitude westerly flow. Therefore, the Meiyu frontal zone is a zone of huge moisture convegence and generation of convective activities (Ninomiya, 1989).

Although it may be seen from the distribution of frontal system that the Meiyu front is also a system togather with the Baiu front in Japan and the Changma front in the Korean Peninsula. However, either from large–scale or from meso–scale characteristics, it may be found that the structure of Meiyu front in China is different from the Baiu front in Japan and the Changma in Korea (Kato, 1989; Ding, 1992; Lu and Chung, 1995). At the mature stage of the Meiyu season, the low–level southerly wind component toward the Meiyu front in the Yangtze River and the Huaihe River valley is stronger than that in South Korea and Japan. Moreover, the moisture content in the continent to south of the subtropical high is also larger than that in South Korea and Japan.

The Meiyu front is main rain band in the East Asian summer monsoon region, and its strength directly influences the occurrence of drought and flood disasters in the East Asian monsoon region. Tao and Chen's (see Tao and Chen, 1985) investigations showed that in the summers with the strong Indian monsoon, the Meiyu front used to be weak, and even there is no Meiyu in some summers.

From the above analyses, it may be seen that although both the East Asian summer monsoon and the Indian monsoon belong to the Asian monsoon system, the characteristics of the East Asian summer monsoon are different from that in the Indian summer monsoon either in their components, structure or in the water vapour transport and rainfall. Therefore, the East Asian summer monsoon and the Indian summer monsoon are two subsystems of the Asian monsoon, which are linked to each other on one hand, but have different features and are relatively independent on the other hand.

3. INTERANNUAL AND INTRASEASONAL VARIABILITIES OF THE EAST ASIAN SUMMER MONSOON AND THEIR MECHANISM

As described above, since the summer monsoon in East Asia is influenced not only by the Indian monsoon, but also by the western Pacific subtropical high, its interannual and intraseasonal variabilities are large and complex.

3.1 *Interannual Variability of the East Asian Summer Monsoon and Its Causes*

The interannual variability of the summer monsoon in East Asia is large, and the occurrence frequency of the summer drought and flood disasters is also large there, especially in the area from the Yangtze River valley to south Japan through South Korea. Recent studies have shown that there is an obvious biennial oscillation in the summer monsoon rainfall in East Asia (Miao and Lau, 1990; Lau et al., 1992; Yin et al., 1996), especially in the Yangtze River and the Huaihe River valley, the Yellow River valley and North China.

Concerning the causes of the East Asian summer monsoon, previously, many investigations emphasized the thermal effect of the Tibetan Plateau on it (Ye and Gao, 1979; Nitta 1983; Luo and Yanai, 1984; Huang, 1984, 1985) and pinted out that the heating anomaly over the Tibetan Plateau has a large impact on the Asian summer monsoon. Many observational facts have shown that the tropical western Pacific is a region of the highest SST in the global sea surface, thus, this region is known as " the warm pool". Because the warm pool has the highest SST, the air–sea interaction is very strong in the region. Moreover, due to the ascending branch of the Walker circulation over this area, the convergence of air and moisture leads to strong convective activities and heavy precipitation (Cornejo–Garrido and Stone, 1977, Hartmann et al., 1984). The studies by many scholars (Nitta, 1987; Huang and Li 1987; Huang and Lu; Kurihara, 1989) showed that the thermal states in the warm pool and the convective activities over the warm pool may play an important role in the interannual variability of the East Asian summer monsoon. Huang and Sun (1992), Huang and Sun (1994a) made systematical investigations on the influence of the thermal state of the warm pool and the convective activities around the Philippines on the interannual anomalies of the East Asian monsoon circulation from the observed data and the analyses of dynamical theories. These studies showed that, as shown in Fig.2, there is a teleconnection pattern of the summer circulation anomalies over the Northern Hemisphere, i.e., the so–called the East Asia / Pacific teleconnection pattern (EAP pattern), which is also called as the East Asia / North America teleconnection pattern by Lau and Shen (1992). It is shown from this teleconnection pattern that the wavetrain can propagate from Southeast Asia to the western coast of North America through East Asia during the Northern Hemisphere summer. This teleconnection pattern may greatly influence the intraseasonal variability of the East Asian summer monsoon.By numerical simiulations, Huang and Lu (1989), Nikaido (1989) demonstrated that this East Asia / Pacific pattern teleconnection is associated with the convective activities in the tropical western Pacific.

The ENSO cycle is one of the most striking phenomena in the tropics. Many investigations have shown that the ENSO cycle greatly influences the Asian monsoon (see Mooley and Parthasarathy, 1983; Rasmusson and Carpenter, 1983; Khandekar and Neralla, 1984). They have found that the weak Indian summer monsoon tends to occur in El Nino year. Studies by Fu and Teng (1993) and by Huang and Wu (1989) have also shown that the summer monsoon rainfall anomalies in East Asia may depend on the stage of ENSO cycle. Huang and Wu's

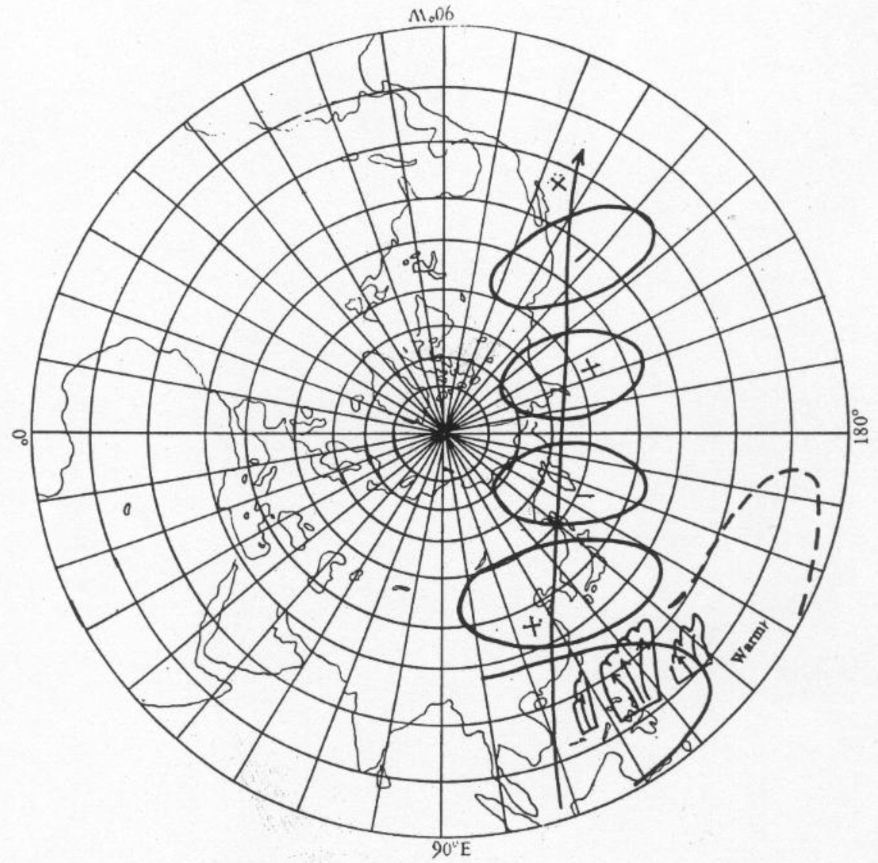

FIGURE 2. Schematic map of the East Asia / Pacific pattern teleconnection of the atmospheric circulation anomalies in the Northern Hemisphere summer.

investigation showed that during the developing stage of an ENSO event (Figure 3a), flood tends to occur in the Yangtze River and the Huaihe River basin of China, South Korea and Japan, but drought may be caused in North China, for example, in the summers of 1980, 1982 / 83, 1986 / 87, 1991, severe floods occurred there. On the contrary, during the decaying stage of an ENSO event (Figure 3b), drought tends to occur in the Yangtze River and the Huaihe River basin of China, South Korea and Japan, but rainfall may be normal or above normal in North China, for example, in the summers of 1981, 1985, 1988 and 1994. Zhang et al. (1996) also pointed out that southerly wind anomalies appear in the lower troposphere along the coast of East Asia during the mature phase of ENSO events.

The interannual variability of Asian monsoon is also influenced by the Eurasian snow cover and the land–sea thermal contrast. Hahn and Shukla (1976), Dickinson (1984) investigated the relationship between the Indian monsoon rainfall and the Eurasian snow cover. Their investigations showed that there is an inverse relationship between these two quantities. This inverse relationship has been demonstrated by Khandekar (1991) using more new data. The studies by Chen et al. (1979, 1981), Wei and Luo (1996) showed that the snow cover on the Tibetan Plateau influences the rainfall in the middle and lower reaches of the Yangtze River.

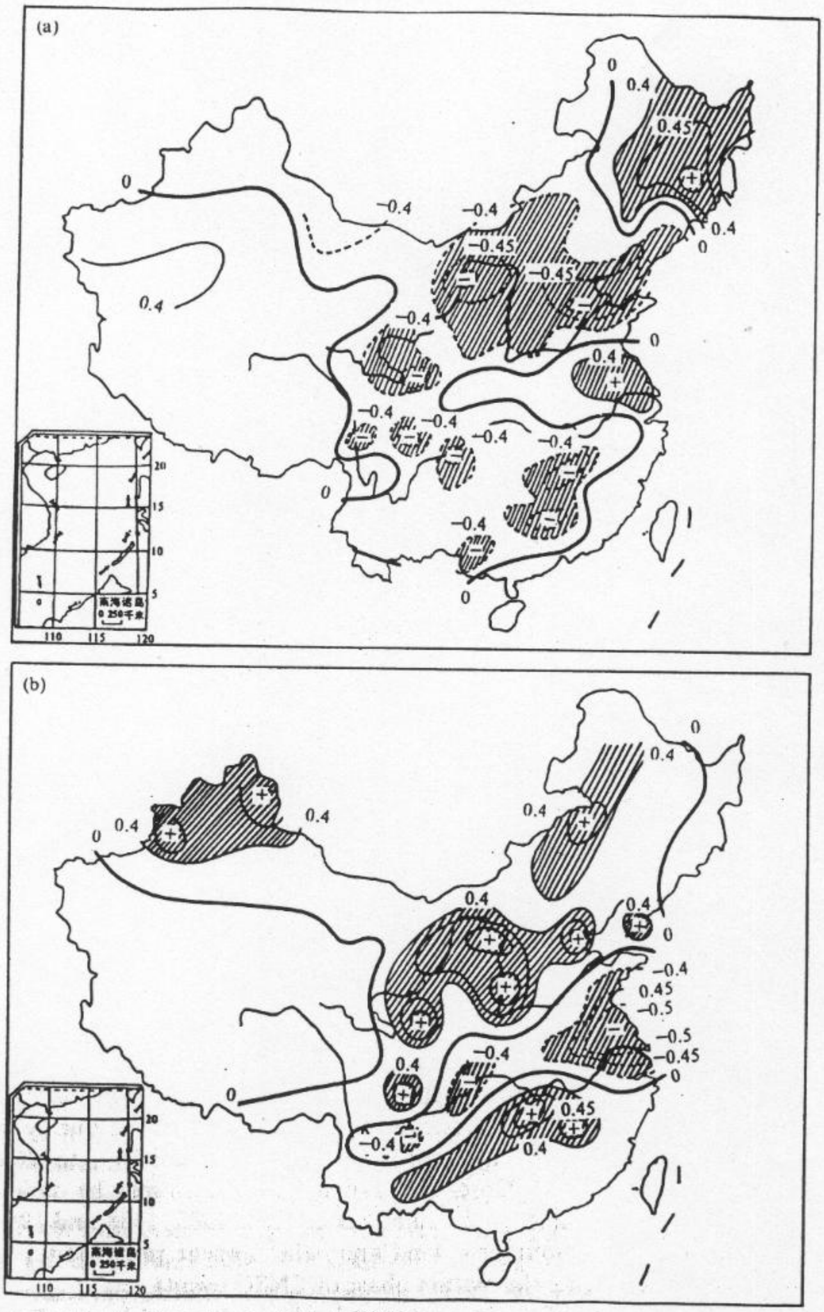

FIGURE 3. Distribution of the SST in the equatorial eastern Pacific and the summer rainfall in China during different stages of ENSO cycle. (a) Developing stage; (b) decaying stage of ENSO cycle.

From the above mentioned advances of studies, it may be seen that the interannual variations of the East Asian summer monsoon are associated with the thermal state of the western Pacific warm pool and the convective activities around the Philippines, the different stages of ENSO cycle, the snow cover on the Eurasian continent and the Tibetan Plateau. Of course, the intensity of the East Asian winter monsoon also influences the East Asian summer monsoon (Sun Bomin et al., 1996; Sun Shuqing et al., 1996).

3.2 *Intraseasonal Variability of the East Asian Summer Monsoon*

Seen from the climatological–mean case, the rain band of the East Asian summer monsoon is located to the south of the Yangtze River during the period from May to the first 10 days of June, and then it moves abruptly northward and is located in the Yangtze River and the Huaihe River basin of China, South Korea and Japan in mid–June. This is the beginning of the Meiyu season in China, the Changma season in South Korea and the Baiu season in Japan. Moreover, the rain band again moves abruptly northward to North China in mid–July. This makes the Meiyu season end in the Yangtze River basin, and the rainy season begins in North China and Northeast China. Obviously, the abrupt movement of the rain band is closely associated with the abrupt northward shift of the western Pacific subtropical high. Yeh et al. (1959) first dircovered the abrupt change of the circulation over East Asia during early and mid–June. This abrupt change of planetary–scale circulation will bring the onset of the East Asian summer monsoon. Later on, Krishnamurti and Ramanathan (1982), McBride (1987) also pointed out the abrupt change of the Indian summer monsoon and the Australian summer monsoon. Huang et al. (1992), Huang and Sun (1994) showed that there is a close relationship between the anomalous northward shift of the western Pacific subtropical high and the convective activities around the Philippines. In the summer with the strong convective activities around the Philippines, the abrupt northward shift of the western Pacific subtropical high is obvious in early or mid–June, and the East Asian summer monoson rainfall may be weak in the Yangtze River and the Huaihe River basin of China, South Korea and Japan. On the contrary, in the summer with the weak convective activities around the Philippines, the abrupt northward shift of the western Pacific subtropical high is not obvious, and the summer monsoon rainfall may be strong in the Yangtze River and the Huaihe River basin of China, South Korea and Japan.

For the above–mentioned relationship between the East Asian summer monsoon and the convective activities around the Philippines and its physical mechanism, Huang and Sun (1992, 1994a) showed that there are close relationships among the thermal states of the northern part of the warm pool, the atmospheric convective activities around the Philippines, the western Pacific subtropical high and the East Asian summer monsoon. As shown in Figure 4a, when the SST in the warm pool is above normal, i.e., the warm sea water is accumulated in the western Pacific warm pool, and a cold tongue extends westward from the Peruvian coast along the equatorial eastern Pacific, in this case, the convective activities are intensified from the Indo–China Peninsula to the east of the Philippines, the western Pacific subtropical high may shift unusually northward, therefore, the summer monsoon rainfall may be below normal in East Asia, especially in the Yangtze River and the Huaihe River basin of China, South Korea and Japan. On the contrary, as shown in Fig.4b, when the SST in the warm pool is below normal, i.e., the warm sea water extends eastward from the warm pool along the equatorial western Pacific, in this case, the convective activities are weak around the Philippines and are intensified over the equatorial central Pacific near the dateline, the western Pacific subtriopical high may shift southward, thus, the summer monsoon rainfall may be above normal in East Asia, especially severe floods may occur in the Yangtze River and the Huaihe River basin of China, South Korea and Japan.

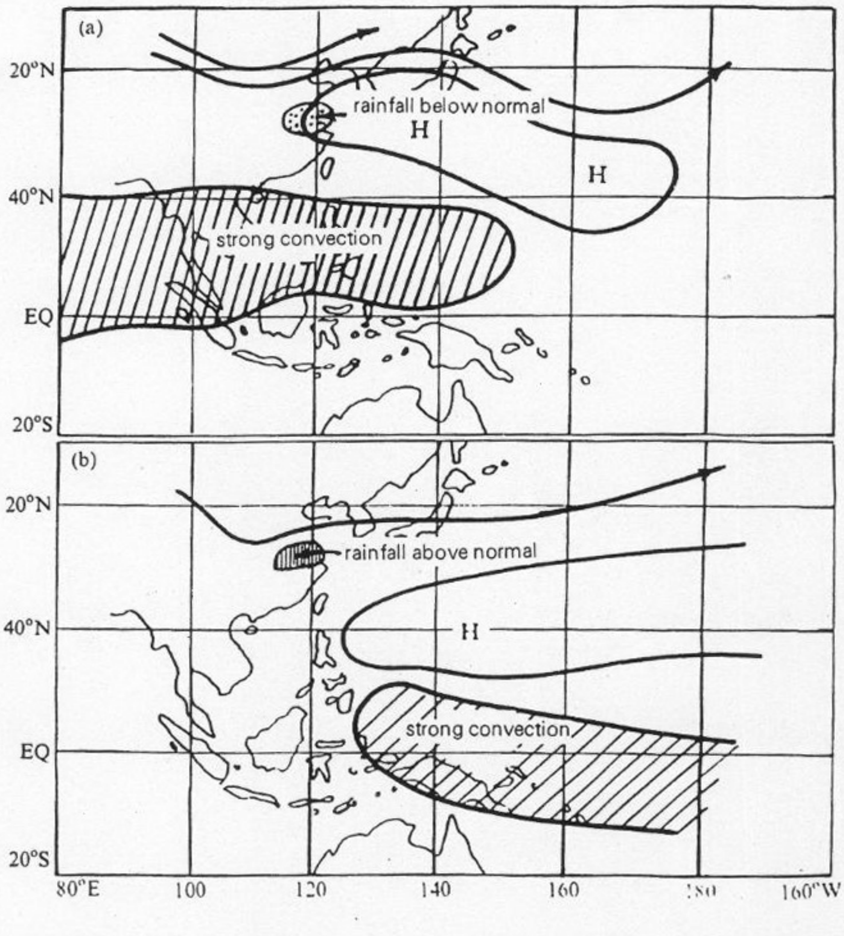

FIGURE 4. Schematic map of relationship between the SST in the western Pacific warm pool, the convective activities around the Philippines, the western Pacific subtropical high, the summer monsoon rainfall in East Asia. (a) Warming case of the western Pacific warm pool; (b) cooling case of the western Pacific warm pool.

Many scholars' investigations pointed out that the influence of the sea temperature in the tropical western Pacific and the convective activities over the tropical western Pacific on the intraseasonal variability may be through the 30–60 day oscillation. The investigations by Sun and Huang (1995), and Li (1996) showed the intraseasonal variability of the East Asian summer monsoon is associated with the 30–60 day oscillation. Huang's (1994) study also showed that the 30–60 day oscillation of the East Asian summer monsoon may be associated with the propagation of the 30–60 day oscillation from the tropical western Pacific to the East Asian monsoon region.

4. EFFECT OF THE EAST ASIAN MONSOON ON GLOBAL CLIMATE VARIABILITY

Recent investigations showed that the interaction between Asian monsoon and ENSO cycle is very obvious. The diagnostic and modelling studies have revealed that the variabilities of the Asian summer monsoon activity have a significant effect on the atmosphere / ocean coupled system in the equatorial Pacific. Yamagate and Matsumoto (1989), Yasunari (1990), Yasunari and Seki (1992) pointed out that the weaker (stronger) Asian summer monsoon seems to lead an anomalous state of the atmosphere / ocean sytem, which is favorable for the El Nino (or anti–El Nino or La Nino) in the equatorial eastern Pacific. Li (1992), Huang et al. (1992, 1996a, 1996b) suggested from the analyses of observed data that the anomalous East Asian monsoon may play an important role for the occurrence of ENSO events. As shown in Fig.5, the westerly anomalies over the tropical western Pacific have a significant dynamical effect on the formation of El Nino events in the equatorial eastern Pacific. The westerly anomalies over the equatorial western Pacific may originate not only from the South Asian monsoon region, but also from the East Asian monsoon region. The southward propagation of the westerly wind anomalies in the lower troposphere over the East Asian monsoon region may lead to the westerly wind anomalies over the tropical Pacific through the EU pattern teleconnection.

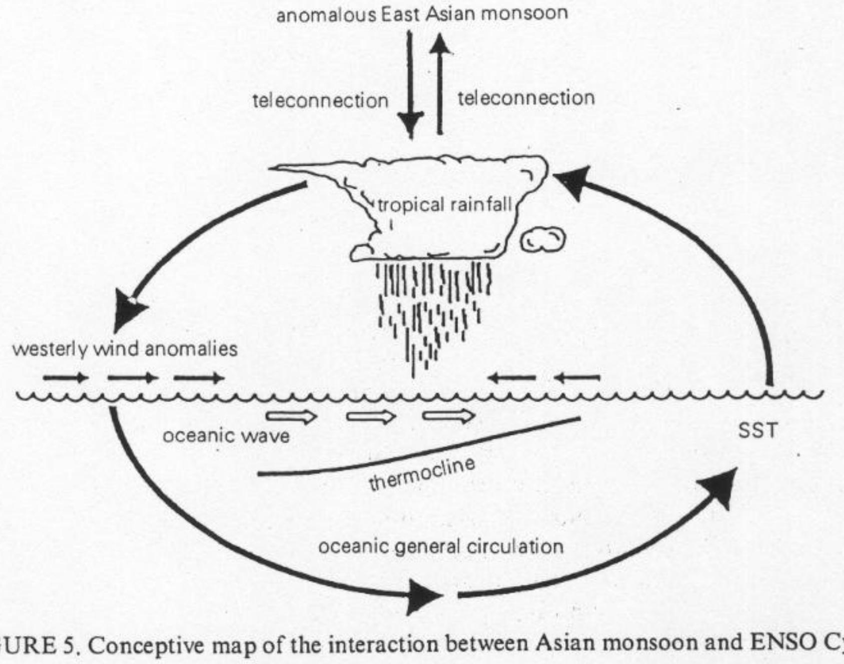

FIGURE 5. Conceptive map of the interaction between Asian monsoon and ENSO Cycle.

Li (1988, 1990) studied deeply the triggering effect of the East Asian winter monsoon on the ENSO event in the equatorial Pacific and pointed out that the strong winter monsoon in East Asia will bring frequently the strong cold surge. This can intensify the convective activitites over the equatorial western Pacific. This, in turn, may strengthen the 30–60 day oscillation in the atmospehre over the tropical western Pacific, and the intensified low–frequency oscillation may trigger an ENSO event.

5. MODELLING AND PREDICTABILITY OF THE EAST ASIAN SUMMER MONSOON

The recent great progresses in the GCMs have been leading the modelling and prediction of the East Asian summer monsoon to be preliminarily successful (Palmer, 1992). Zeng et al.

(1988) successfully simulated the abrupt transition from the winter state to the summer state of the monsoon circulation over East Asia. Huang and Lu (1989), Huang and Sun (1992) have successfully made the numerical simulations of the influence of a thermal anomaly in the northern part of the western Pacific warm pool on the summer monsoon over East Asia using the IAP–GCM, Moreover, the teleconnection pattern of East Asia / Pacific (EAP pattern) influencing the summer monsoon circulation anomalies over East Asia was also successfully simulated . Nikaidou (1989) also simulated the EAP pattern using the MRI–GCM. Besides, the dynamical and thermal effects of the Tibetan Plateau on the Asian summer monsoon variability and the influence of snow cover, albedo and soil wetness in land surface on the East Asian summer monsoon have been well simulated by many studies using the GCMs (Yasunari, 1991; Kuo and Qian, 1982; Wu et al., 1995). These simulations explained that the elevation, thermal state, snow cover, albedo and soil wetness of the Tibetan Plateau have a great influence on the East Asian summer monsoon.

However, the skills in the simulation of the Asian summer monsoon rainfall with GCMs or climate models have not increased substantially during the recent years (Gadgil et al., 1992). All GCMs still have large systematic errors not only in the regional scale, but also in the planetary–scale. The systematic errors may be sensitive to the heat fluxes at the sea surface of the western Pacific warm pool, the convective activities in the tropics and the monsoon region and the calculating schemes of land surface processes (WMO, 1992). Huang, Chen and Cheng (1996) pointed out that the simulation of the East Asian summer monsoon rainfall and circulation is very sensitive to the cumulus parameterization scheme used in climate models. The simulated result of the summer monsoon rainfall and circulation with a cumulus parameterization scheme is very different from that simulated by using other schemes.

Because the interannual and intraseasonal variabilities of the East Asian monsoon are very complex, up to now, the prediction methods by experiences and statistics are still applied widely to the seasonal prediction of the summer monsoon rainfall in China, Korea and Japan (See Huang et al., 1990; Kurihara, 1989; Moon 1996). However, the prediction accuracies by these methods are unstable, thus, many scientists are making efforts to search an effective prediction method using dynamical and numerical models. Zeng et al. (1990) first made a try of the seasonal prediction of the summer monsoon rainfall in East Asia, and their result was hea rtening. Later on, Zeng et al. (1994) and Huang et al. (1996) also made a series of the seasonal forecasting experiments of the summer monsoon rainfall in East Asia by the IAP–Coupled GCM and the IAP–GCM with a filtering scheme, respectively. Their investigations explained that GCM or coupled GCM may be one of the effective seasonal prediction methods for the East Asian summer monsoon rainfall.

However, in the study of the predictability of the East Asian summer monsoon variability, because it is necessary not only to clearly understand the regularity, causes and physical factors of the East Asian summer monsoon variability, but also to well design a numerical model describing the East Asian monsoon variability, in which the various processes in the atmosphere and the ocean as well as the land–surface processes can be described accurately, the predictability of the interannual variability of the East Asian summer monsoon is a very difficult research issue.

6. PROBLEMS ON THE EAST ASIAN MONSOON TO BE STUDIED FURTHER

It is seen from the above review that great progresses have been made in the research on the East Asian summer monsoon. However, many problems on the variabilities and their causes of the East Asian summer monsoon are still not clear and therefore need to be studied further.

(1) On the monsoon index: The monsoon index is a criterion measuring the strength of monsoon, and it is necessary for the studies of the interannual variability of monsoon. Up to now, there are two definitions on the Asian monsoon index: one is defined from the thermaodynamical elements, such as, Tao and Chen (1987) defined a monsoon index with the strength of monsoon rainfall, and Tu and Huang (1944) defined a monsoon index with θ_{se} in a monsoon region, while Murakami and Matsumoto (1994) defined a monsoon index from OLR; another is defined from the dynamical elements, such as, Webster and Yang (1992), Zeng et al., (1994) defined a monsoon index from the distributions of the wind fields in high and low layers of the atmosphere in a monsoon region. There are advantages and disadvantages in those definitions. The former is easily influenced by local thermodynamical condition, but the later is more suitable for the South Asian monsoon region. Due to the difference between the South Asian monsoon and the East Asian monsoon, the East Asian summer monsoon rainfall used to be weak in the summer with the strong South Asian monsoon. Moreover, since the meridional component of the East Asian summer monsoon is larger, it may be not suitable to define the strength of the East Asian summer monsoon with the zonal component of wind field. Therefore, it is a problem to be studied further how do define a monsoon index to be suitable for the East Asian monsoon from the combination between thermodynamics and dynamics.

(2) About the interaction between the monsoon action and the intraseasonal oscillation in the East Asian monsoon region: As mentioned in Section 3, many investigations showed that the low–frequency in the tropics and mid–latitudes has an important impact on the East Asian monsoon, while the East Asian monsoon actions including the onset, active and break of the monsoon also influence the low–frequency. The interaction between them is not clear yet so far. Therefore, the study of the monsoon actions and the low–frequency oscillation in the atmosphere is also an important issue, and it is also an important issue of Climate Variability and Predictability Programme (CLIVAR).

(3) On the intenrnal–dynamical process of monsoon: there are conplex dynamical and thermal processes in the monsoon system. The monsoon system includes the systems with different spatial and temporal scales, and the interaction between them has an important impact on the monsoon actions. Moreover, the dynamical stability of the monsoon circulation has also an important effect on the monsoon actions and its maintenance. However, recently, the study on this problem is not much. Therefore, the internal–dynamical process of monsoon system should be deeply studied further.

(4) Concerning the interaction between monsoon and ENSO cycle: The different stages of ENSO cycle influence the East Asian summer monsoon circulation and rainfall. However, what physical process is the East Asian summer monsoon influenced through? It is not clear yet so far. Moreover, the anomalous East Asian monsoon also influences the occurrence of ENSO event. It influences the westerly wind anomalies over the equatorial western and central Pacific through the low–frequency oscillation or other physical process. This problem should be studied further from the analyses of observed data, the dynamical theories and the numerical simulations in detail.

(5) Concerning the simularion and predictability of the East Asian summer monsoon: The observed facts of the East Asian summer monsoon rainfall. This may be due to the following reasons: Firstly, the multi–scale characteristics of monsooon system and their interactions are not known clearly yet. Thus, it is difficult to design the convective parameterization scheme to be suitable for the convective activities in the East Asian monsoon region. The second, the snow cover, albedo and the hydrological cycle process in the land–surface of monsoon region are also not clear so far. Thus, this may make the description of the land–surface process in models not accurate. The third, the description of heat flux in the sea surface and

the cumulus convective parameterization scheme in the tropical western Pacific need to be improved further. Therefore, it is necessary to proceed to some intensive observational experiments so that the multi–scale characteristics of monsoon system and the relationship between the monsoon rainfall and the flow flux of river, runoff and soil moisture can be understood in detail. In order to understand deeply those issue, the Global Energy and Water Cycle Experiment (GEWEX) was proposed as a major part of WCRP after 1995, and the GEWEX Asian Monsoon Experiment (GAME) was put forward as a major part of GEWEX. It is possible to determine the role of the Asian monsoon in the global climate system and to propose a better cumulus parameterization scheme and description of the land–surface process to be suitable for the summer monsoon in East Asia. Thus, a better atmosphere–ocean–land coupling model needs to be established to simulate the variabilites of the East Asian monsoon.

(6) As for the interdecadal variability of the East Asian monsoon: The observations showed that the East Asian monsoon has a large interdecadal variability. However, its causes are not clear so far, and the study on it is also scarce. Moreover, as shown in the previous section, the simulation and prediction of the monsoon variabilities on seasonal, interannual and interdecadal time–scales are still a difficult research issue. Therefore, the CLIVAR has been proposed in the international academies and will be proceeded for 15 years. The study on the interannual and interdecadal variabilities of the monsoon system will be one of the main objectives of CLIVAR. We can believe that after the research programme of CLIVAR is implemented, it is possible that the study on the interdecadal variability of the East Asian summer monsoon will get some progresses.

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