A Study of the Teleconnections in the Asian-Pacific Monsoon Region*

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ABSTRACT

The interactions among the Asian-Pacific monsoon subsystems have significant impacts on the climatic regimes in the monsoon region and even the whole world. Based on the domestic and foreign related research, an analysis is made of four different teleconnection modes found in the Asian-Pacific monsoon region, which reveal clearly the interactions among the Indian summer monsoon (ISM), the East Asian summer monsoon (EASM), and the western North Pacific summer monsoon (WNPSM). The results show that: (1) In the period of the Asian monsoon onset, the date of ISM onset is two weeks earlier than the beginning of the Meiyu over the Yangtze River Basin, and a teleconnection mode is set up from the southwestern India via the Bay of Bengal (BOB) to the Yangtze River Basin and southern Japan, i.e., the "southern" teleconnection of the Asian summer monsoon. (2) In the Asian monsoon culmination period, the precipitation of the Yangtze River Basin is influenced significantly by the WNPSM through their teleconnection relationship, and is negatively related to the WNPSM rainfall, that is, when the WNPSM is weaker than normal, the precipitation of the Yangtze River Basin is more than normal. (3) In contrast to the rainfall over the Yangtze River Basin, the precipitation of northern China (from the 4th pentad of July to the 3rd pentad of August) is positively related to the WNPSM. When the WNPSM is stronger than normal, the position of the western Pacific subtropical high (WPSH) becomes farther northeast than normal, the anomalous northeastward water vapor transport along the southwestern flank of WPSH is converged over northern China, providing adequate moisture for more rainfalls than normal there. (4) The summer rainfall in northern China has also a positive correlation with the ISM. During the peak period of ISM, a teleconnection pattern is formed from Northwest India via the Tibetan Plateau to northern China, i.e., the "northern" teleconnection of the Asian summer monsoon. The above four kinds of teleconnections reflect the links among the Asian monsoon subsystems of ISM, EASM, and WNPSM during the northward advancing march of the Asian summer monsoons.

Key words: Asian-Pacific monsoon region, Indian summer monsoon (ISM), western North Pacific summer monsoon (WNPSM), Meiyu over the Yangtze River Basin, northern China rainy season, teleconnection mode

1. Introduction

In the early 1980s, since Wallace and Gutzler (1981) found five kinds of teleconnection modes in the Northern Hemisphere winter by the method of one-point correlation of height fields, the concept of the teleconnection has attracted extensive attentions of meteorologists. Hoskins and Karoly (1981) found the teleconnection mode linking with the propagation of the Rossby waves, indicating that the five kinds of teleconnection modes may be a certain propagating pattern of the stationary Rossby waves. However, there are some kinds of typical teleconnections in the peak period of the Asian-Pacific summer monsoon, which are much different from those five winter teleconnections. Correlation computations by Nitta (1987) between 5-day mean tropical cloud amount and 500-hPa geopotential height show that there exist teleconnection wave trains of geopotential height emanating from the heat source region near the Philippines to North America, which is known as Pacific-Japan (PJ) teleconnection pattern, or East Asian-Pacific (EAP) teleconnection pattern. In mid-summer, the convective activities in the Philippine Sea may be the wave source

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to generate the PJ wave train, and the propagation of the PJ wave train can lead to sizzler days in Japan. Huang and Ru (1989) and Nikaido (1989) validated by numerical simulations that the EAP teleconnection is related to the western Pacific convective activities, and pointed out when the convective activities near the Philippine Sea is stronger than normal, the EAP teleconnection pattern is more significant. Huang and Wu (1989) indicated that the EAP teleconnection pattern can vary with different stages of ENSO, and the EAP propagation has a great impact on the flood/drought in eastern China. With regard to the influence of ENSO on the climate anomaly in China, Wang et al. (2000) suggested another teleconnection mode between the central and eastern Pacific and East Asia (PEA) during the extreme phases of ENSO cycle. This PEA teleconnection is confined to the lower troposphere when a strong warm or cold event matures, and persists until the following early summer, the decaying phase of ENSO. The East Asian climate change is influenced by the SST anomalies in the central and eastern Pacific through the PEA teleconnection. Using the South China Sea monsoon (SCSM) index (defined as the divergence difference between the higher and lower levels of the troposphere) and numerical simulations, Li and Zhang (1999) found that the teleconnection from western Pacific via North Pacific to North America (EAP) becomes very significant and extends anomalously northward when the SCSM is stronger than normal; while the position of the EAP pattern shows a relatively southern anomaly in the weak SCSM years. Based on the precipitation and 500-hPa geopotential height data, Lau et al. (2002, 2004) investigated the teleconnection between the East Asian summer monsoon (EASM) and the precipitation in North America, and then they suggested two new teleconnection patterns−Tokyo-Chicago Express (from Japan and Northeast China, crossing North Pacific to western Canada, the northern Great Plains, and mid-west US) and Shanghai-Kansas Express (from central East Asia across North Pacific to North America).

The teleconnections related to the Indian summer monsoon (ISM) also have great impacts on the climate anomaly in the Asian monsoon region. Guo et al. (1988, 1992) and Liang (1988) found that there exist significant positive correlations between ISM rainfalls and the precipitation in northern China. Then Kripalani and Kulkarni (1997, 2001) revealed that the rainfall variations over northern China (and southern Japan) are in-phase (out-of-phase) with the ISM rainfall based on various kinds of climatic data. By a comparison of the impacts of ISM on the Asian climate with that of WNPSM, Wang et al. (2001) pointed out that the teleconnection associated with the anomalous WNPSM is more remarkable in terms of the extent and intensity. During a strong WNPSM, a pronounced wave train pattern, seen in the lower, middle, and upper troposphere, emanates from the WNP, crosses the North Pacific and extends to North America. Enomoto et al. (2003) found that an equivalently-barotropic anticyclone is formed in upper subtropical jet stream near Japan in August, which causes the northern extension of the Bonin high. It is the result of the propagation of stationary Rossby waves in the jet stream along the Asian jet in the upper troposphere (the Silk Road pattern). Recently, a climatological global teleconnection (CGT) is found by Ding and Wang (2005, 2007) in the Northern Hemisphere summer. They indicated that the circulation anomaly over the North Atlantic and European continent may trigger the Asian subtropical jet circulation anomaly, forming the teleconnection wave train from Northwest India/Pakistan crossing East Asia and North Pacific to North America.

From the above findings we can see that these typical teleconnection wave trains have very significant impacts on the weather and climate anomalies in the Asian-Pacific monsoon region. The very reason they come into being is the interaction between the upstream and downstream which triggers the anomalous circulations of the Northern Hemisphere summer. The origins of most of the teleconnection patterns are normally regions of anomalous heat sources produced by significant monsoon rainfalls or tropical convective activities that can generate the Rossby wave train to propagate to North America via North Pacific through the wave guide of the mid-latitude westerly jet stream (such as the EAP pattern). The other possible mechanism is through heating induced meridional circulation that perturbs mid-latitude jet stream, which in turn excited optimum downstream circulation anomaly mode (such as the CGT pattern)(Ding, 2007).

The Asian-Pacific monsoon, which is divided into three main subsystems: ISM, EASM, and WNPSM by the characteristics of wind and precipitation, is the most significant and largest monsoon system in the world (Wang et al., 2001, 2002, 2003; Fig.1). The eastern China belongs to the EASM region, with its floods/droughts closely related to the teleconnections generated from the monsoon rainfall. Moreover, the ISM and WNPSM also have important impacts on the eastern China rainfall, but there are few researches on the teleconnections associated with summer monsoon rainfall over the eastern China in previous studies. Recently, Liu and Ding (2008a, b, c) made a series of researches on the Asian-Pacific monsoon teleconnections related to the precipitation of the eastern China at different time and spaces. Those four different teleconnections found in the Asian-Pacific monsoon region present a more complete understanding of the interactions among the various monsoon subsystems in Asian-Pacific region, and also provide valuable reference for mid- and long-term forecasts for the eastern China summer rainfall. Combined with the previous researches at home and abroad, the four different teleconnections will be mainly discussed in the present paper.

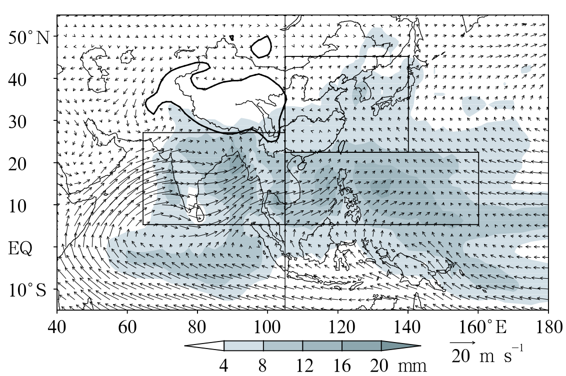

Fig.1. Climatological July-August precipitation (shaded, unit: mm) and 925-hPa wind field (unit: m s^{-1}) in the Asian-Pacific monsoon region. The solid square-frames denote the ISM area (5°-27.5°N, 65°–105°E), the EASM area (22.55°– 45°N, 105°–140°E), and the WNPSM area (5°–22.5°N, 105°-160°E), respectively.

The present paper includes 6 sections. Section 1 is an introduction. Section 2 depicts the teleconnection between the ISM rainfall and the precipitation over the Yangtze River Basin in the monsoon onset period. Section 3 discusses the teleconnection between WNPSM and the Yangtze River rainfall. Sections 4 and 5 consider the northern China rainy season, discussing the teleconnections between the WNPSM and the northern China rainfall, and the teleconnection between the ISM and the northern China rainfall, respectively. The last section is the conclusion and discussion.

2. Teleconnection between the ISM onset and the Meiyu over the Yangtze River Basin

2.1 Relationship between southwest Indian precipitation and the Meiyu over the Yangtze River Basin

Ye et al. (1958) and Tao and Ding (1981) all discovered that the general circulation over East Asia undergoes a sudden seasonal change in June every year. The subtropical upper westerly belt and its associated jet stream systems suddenly jump northward, causing the rapid disappearance of the westerly jet stream over South Asia and the building up of an upper tropical easterly jet stream at low latitude; the upper South Asian high (SAH) moves northward, too. At the same time, the ISM commences in the lower troposphere, and the Meiyu over the Yangtze River Valley starts subsequently. Considering that the ISM firstly begins over Kerala, southwest India, we calculated the correlation coefficient between precipitation in Kerala and that in China from June to September, finding that Kerala's precipitation is positively correlated to the precipitation over the Yangtze River Basin (Fig.2a). Pentad mean precipitation data by CMAP (CPC Merged Analysis of Precipitation) are also used to validate the positive correlation between the southwest Indian rainfall and the Meiyu (Fig.2b), and the southwest-northeastward teleconnection mode from

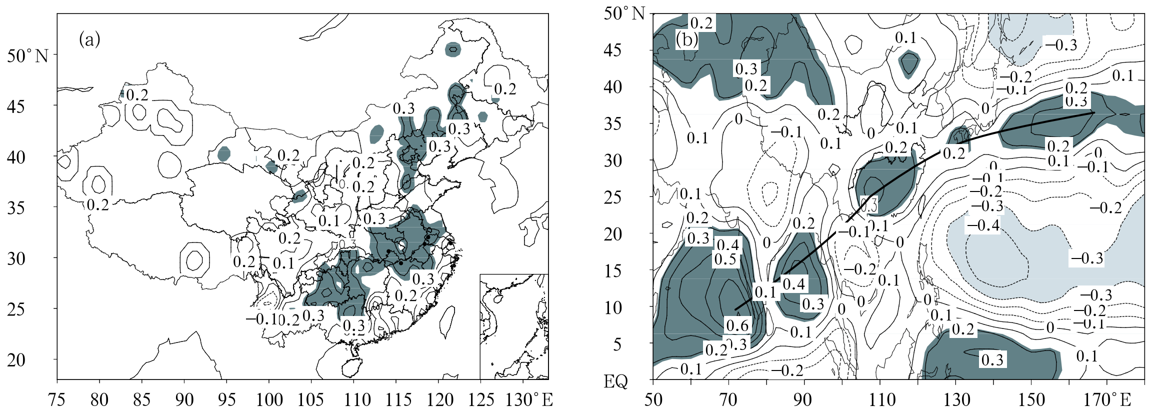

Fig.2. Correlation between the precipitation in Kerala from June to September and 160 stations precipitation in China (a) and CMAP in the Asian monsoon area (b) (Liu and Ding, 2008a). Correlations at the significant level of α=0.05 are shaded.

southwestern India via the Bay of Bengal (BOB) to the Yangtze River Basin and southern Japan is exhibited in Fig.2b. This teleconnection mode makes the primary precipitation centers in the Asian monsoon region connected and correlated well, which suggests that although the ISM and the East Asian summer monsoon (EASM), both of which belong to the Asian monsoon system, have their own distinct characteristics, they also affect mutually.

In order to elucidate more clearly the relationship between the Meiyu and ISM, a lag-correlation is made to analyze the precipitation in Kerala and East Asia from the 31st to 54th pentad (figures omitted). It is indicated that the pentad mean precipitation in Kerala is most related to the precipitation lagging 3 pentads in the Yangtze River Basin (Fig.3). Besides the Yangtze River Basin, the precipitation in the western coast of India also has significant positive correlations to the rainfall in the BOB and southern Japan, but negative correlations to the Indo-China Peninsula and the western Pacific, thus forming the teleconnection mode from the western coast of India via the BOB to the Yangtze River Valley and southern Japan. The position of the teleconnection mode is just consistent with the "moisture conduit" originating from the Southern Hemisphere moving across the equator along the Somalian coast and down to the Arabian Sea, India, and BOB, then extending northward from the South China Sea (SCS) to eastern China and the western North Pacific (Liu et al., 2006; He et al., 2007). Therefore, we speculate that there is a certain relationship between the "south" teleconnection mode and the "great moisture river", which will be further explained later. Comparing Fig.3 with Fig.2b, we can find that the two modes are similar, but the correlation coefficient in Fig.3 is higher. In addition, due to the northward movement of the large-rainfall belt in India, the correlative area in the western coast of India is farther northern in Fig.3. On the other hand, their similarities also suggest that either from the interannual or intraseasonal scale, the monsoon precipitation in the western coast of India, BOB, the Yangtze River Valley, and southern Japan display very good correlations. Besides, since the ISM sets up, the correlation coefficient becomes most prominent after 3 pentads, i.e., about two-week-long time, and the teleconnection

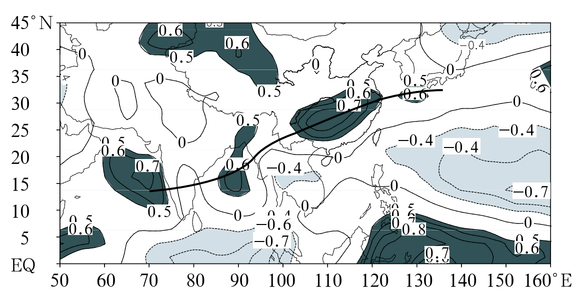

Fig.3. Lag-correlation between the pentad mean precipitation in Kerala from June to September and precipitation in East Asia (Liu and Ding, 2008a). The latter is 3 pentads later than the former; correlations at the significant level of α=0.01 are shaded.

mode becomes most remarkable.

2.2 Relationship between the ISM onset and the beginning of Meiyu

The good correlation between the ISM onset and the Meiyu is not accidental. It is well known that the ISM usually breaks out in the period from the end of May to the beginning of June in Kerala, the southern tip of the Indian continent, and the onset date of ISM is usually determined by the precipitation rate in Kerala and related circulation variation (Fasullo and Webster, 2002; Joseph et al., 2006). While the ISM breaks out, the Yangtze River Valley also starts to enter the Meiyu season, with the easterlies and westerlies jumping northward. Through comparing the beginning date of the Meiyu with the ISM onset over Calcutta, Tao and Chen (1987) pointed out that they occur nearly simultaneously. But their further correlation has not been documented. Choosing the dataset of ISM onset defined by Fasullo and Webster (2002) from 1948 to 1999 (due to the fact that the index considers both the precipitation and atmospheric circulation in the definition, and being the long time series), we calculate the correlation coefficient between it and the beginning date of the Meiyu provided by National Climate Center (NCC) in China (Fig.4), and find that they indeed have very good correlative relationship. The correlation coefficient is 0.3, exceeding the significant level of α=0.05. During the period from 1948 to 1999, the average ISM onset date is June 5th, and the average Meiyu beginning date is June 18th, so the average difference of the two dates is 13 days, which

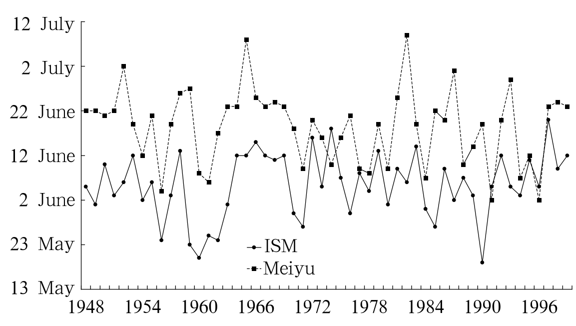

Fig.4. Time series of the ISM onset dates and the Meiyu starting dates over the Yangtze River from 1948 to 1999 (Liu and Ding, 2008a).

also happens to explain why the monsoon precipitation in Southwest India is most related to the precipitation lagging 3 pentads over the Yangtze River Valley.

Through the singular value decomposition (SVD) analysis of 500-hPa height fields in the periods of ISM onset (the left field) and the beginning of the Meiyu (the right field), we obtain the typical spatial distributions (Fig.5 is the spatial structures of the left and right heterogeneous correlation maps of the first mode), which exhibits the mutual influences between ISM and EASM. The variance contribution of the first mode is 94.36%, much higher than other modes; the correlation coefficient of the first mode is 0.742, very remarkable. It is indicated that the ISM indeed has the close relationship to the EASM circulation. The variance contribution of the first left field is 60.02%, while the first right field variance contribution is 32.33%, only a half of the left field, which explains that the coupled mode of the two fields accounts for a greater proportion in the ISM region, because the variation of EASM has more complex characteristics than ISM. The spatial distribution of the first SVD mode reflects the consistent positive correlation between ISM area and EASM area. It is shown that the variation of the 500-hPa height field over the Indian Peninsula influences obviously the Yangtze River Basin, while the change of the height field over the Yangtze River Basin and its south has a close relationship with the ISM onset, too.

All above analysis of the time series and spatial distributions indicate that the ISM onset and the Meiyu beginning in the Yangtze River Basin indeed have a remarkable teleconnection relationship. Liu and Ding (2008a) also indicated that during the two-week period from the ISM onset to the beginning of the Meiyu, the Asian monsoon circulation has experienced a series of changes: the northward movement of the South Asian high (SAH), the onset vortex occurrence, the eastward extension of the stronger tropical westerly belt, the northeastward jump of the western Pacific subtropical high (WPSH), etc. After about two weeks, the upper westerly jet stream and the low level jet have been coupled vertically over East Asia, while the Yangtze River Valley happens to locate in the

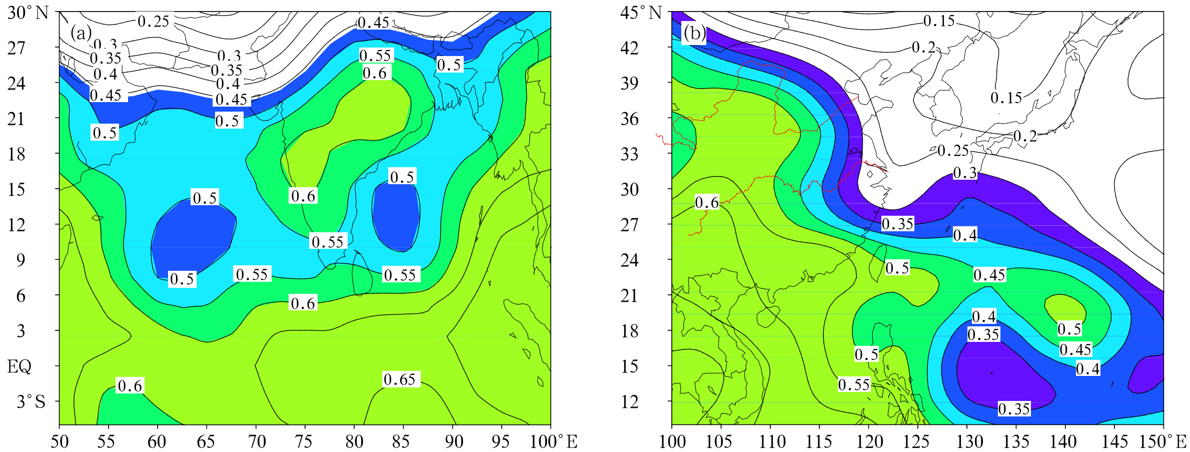

Fig.5. SVD of 500-hPa height field between ISM and EASM areas. (a) The left heterogeneous correlation map of the first mode and (b) the right heterogeneous correlation map of the first mode. Correlations at the significant level of α=0.05 are shaded.

ascending motion area between the upper jet stream and the low level jet, i.e., right of the entrance of the upper jet stream and left of the low level jet. Such a structure of the vertical circulation can trigger the Meiyu onset over the Yangtze River Valley (figure omitted).

3. Teleconnection between WNPSM and the precipitation over the Yangtze River Basin

3.1 Correlation between the precipitation over the key area of WNPSM and over the Yangtze River

It is found that there are two main water vapor sources from the tropical Indian Ocean and western Pacific, respectively, which influence China's summer monsoon rainfall (Ding and Hu, 2003; Liu et al., 2006). Comparing with the impact of the anomalous southwestern water vapor transport which comes from the Indian monsoon region and that of the anomalous southeastern water vapor transport which comes from the western Pacific on summer precipitation in eastern China, Zhang (2001) indicated that the anomalous water vapor transport from southwestern Indian monsoon region is closely correlated to the precipitation over northern China, while the rainfall over the Yangtze River Basin is mainly impacted by anomalous southeastern water vapor transport from the western Pacific, which indicates the relative importance of the western Pacific water vapor transport to China's summer rainfall in the Yangtze River Basin. In the former section, the teleconnection between ISM and the Meiyu over the Yangtze River Basin is demonstrated during the ISM onset. Now we consider the internal relations between WNPSM and the precipitation of the Yangtze River Basin in this section.

The area of the most precipitation in the central part of the WNPSM region is selected as the key area (12.5°–20°N, 130°–150°E), where there is convergence of three flows, that is, westerly monsoon flow from ISM region, two cross-equatorial flows at about 105° and 130°E, and easterly flow along the southern flank of WPSH. This is also the area of the greatest change of the climatological intraseasonal oscillation (CISO) (Wang and Xu, 1997; figure omitted). The WNPSM rainfall usually lasts from June to September (Wang et al., 2005), hence the time series of the standardized precipitation in the key area of the western North Pacific averaged from June to September is defined as the index of the change of WNPSM. The annual variation of WNPSM from 1979 to 2005 is consistent to the index defined by Wang et al. (2001) using the meridional shear of the lower-level zonal wind field. The correlation coefficient of these two indices is 0.73, but the former is more simple and explicit. Through calculating the correlation between the time series of the precipitation of the key area and the 160 stations summer rainfall in China (Fig.6a), it is found that

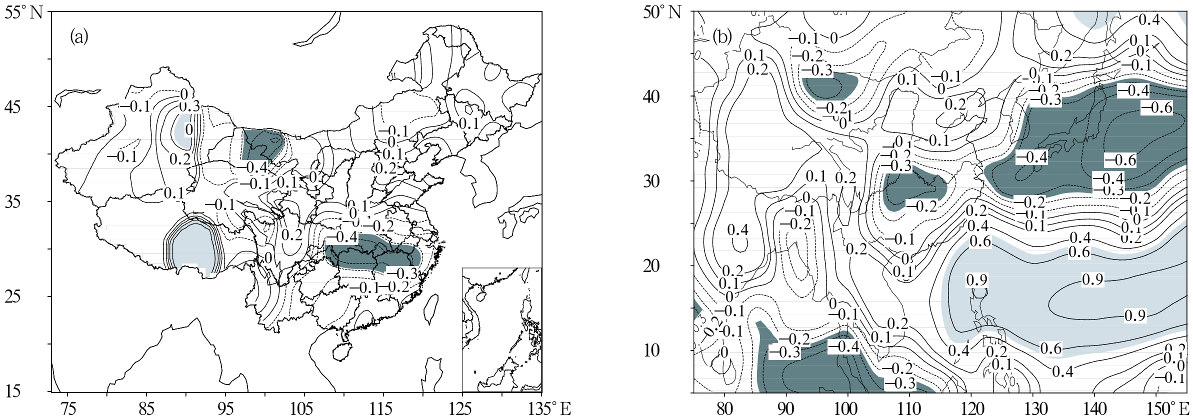

Fig.6. Correlation between the precipitation in the key area of WNPSM from June to September and 160 stations precipitation in China (a) and CMAP in the Asian monsoon area (b) (Liu and Ding, 2008c). Correlations at the significant level of α=0.05 are shaded.

WNPSM and the rainfall over the Yangtze River Basin have a remarkable negative correlation. CMAP summer mean precipitation data are also used to validate the negative correlation between the rainfall over the western North Pacific and that over the Yangtze River Basin (Fig.6b). Wang et al. (2001) also found that WNPSM behaves obviously in opposite phase to the rainfall over the Yangtze River Basin through a comparison of the precipitation difference fields between strong and weak monsoon years.

3.2 Impact of the monsoon intensity on the precipitation over the Yangtze River Basin

The intensity of WNPSM is negatively correlated to the precipitation over the Yangtze River Basin. Comparative analysis of the composite circulation fields of the strong and weak WNPSM can be a good explanation of the impact of monsoon intensity on the rainfall over the Yangtze River Basin. In the strong WNPSM years (Fig.7a), the spatial distribution of the anomalous anticyclonic circulation in the north and the anomalous cyclonic circulation in the south is formed over the western North Pacific at the lower level. That is, when the WNPSM is stronger than normal, the western Pacific high is obviously pushed to higher latitude, while the anomalous large-scale cyclonic circulation lies at the tropical Pacific, which corresponds to the strengthening and eastward extension of the intertropical convergence zone (ITCZ). Under such a situation, the Yangtze River Basin is just located in the divergence area of the easterly flow between those two anomalous circulations; as a result, the precipitation over the Yangtze River Basin is reduced. In the weak monsoon years (Fig.7b), however, the distribution of the anomalous circulations becomes opposite to that in the strong monsoon years. The WPSH system is abnormally southern and western, and the strong southerly flow anomalies form at the south of the Yangtze River. It is the very reason that the Yangtze River Basin is just in the convergence zone of the anomalous southerly and northerly wind, which is favorable for the precipitation over the Yangtze River Basin. Then we consider the vertical circulation. The meridional vertical circulation links the low latitude and the mid- and high-latitude wind fields, playing an important role on the heat, momentum, and water vapor exchange in different latitudes. In the strong WNPSM years (Fig.8a), the East Asian local Hadley circulation becomes weaker than normal, with the anomalous subsidence occurring over the Yangtze River Basin, which makes the summer rainfall in the area decline. However, the local Hadley circulation is just the opposite in the weak monsoon years (Fig.8b). It is stronger than normal, with the subsiding flow at about 20°N turning to north near the ground, causing the southerly wind to strengthen abnormally at the southern part of the Yangtze River Basin, and rendering the anomalous stronger ascending motions occur over the Yangtze River, which then enhances the development of the precipitation in the Yangtze River

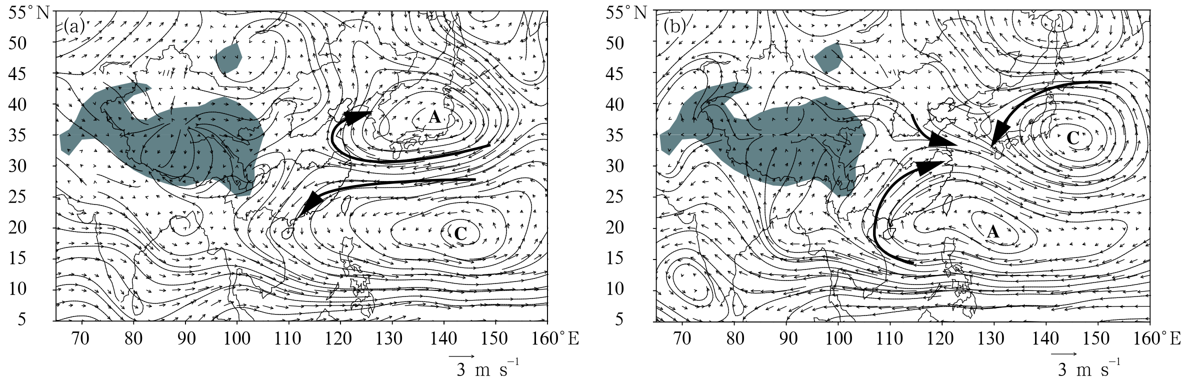

Fig.7. Composite distribution of the 850-hPa wind anomaly in the strong (a) and weak (b) WNPSM years (Liu and Ding, 2008c; unit: m s^{-1}).

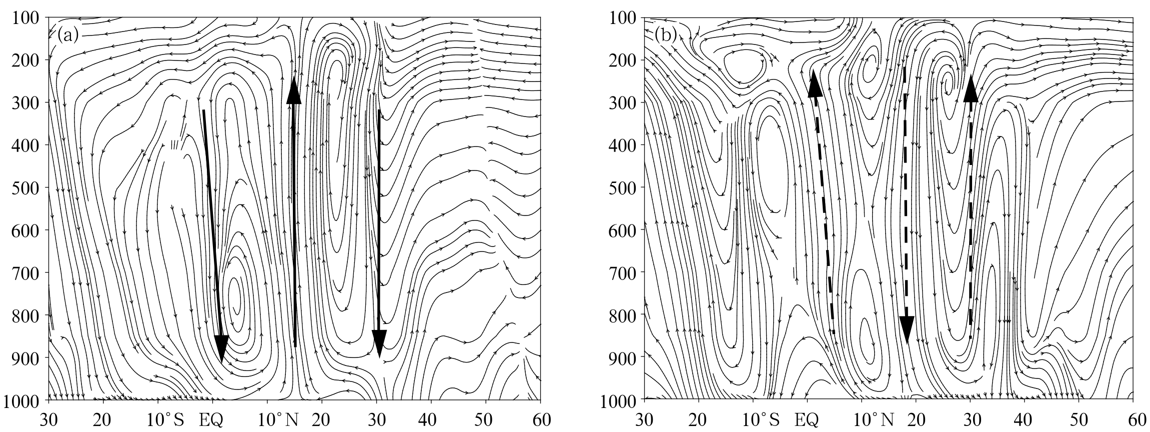

Fig.8. As in Fig.7, but for a composite latitude-altitude cross section of the vertical velocity anomaly in the East Asian region (Liu and Ding, 2008c) (unit of v: m s^{-1}; unit of w: 0.01 Pa s^{-1}).

Basin.

Considering that the intraseasonal oscillation is also an important part of the monsoon variability, as a kind of triggering and modulating factor, the intraseasonal scale change of the monsoon has a significant impact on the outbreak and stepwise advance of the monsoon (Wang and Xu, 1997; Krishnamurti and Subrahmanyan, 1982; Li, 2004). It is found that the CISO displays obvious distinctions in the strong and weak monsoon years, respectively (figure omitted). In the strong WNPSM years, the CISO propagates northward to 25°–30°N, and then shifts significantly to west, from the western North Pacific to northern India, with the few easterly CISO generated from the eastern Indian Ocean. Only the westerly CISO exerts impact from the western Pacific on the Yangtze River Basin, and thus it is not easy to stimulate the precipitation there. In the weak WNPSM years, however, the every western propagation of the westerly CISO from the western Pacific is accompanied with the easterly CISO from the Indian monsoon region. Their convergence at the Yangtze River Basin stimulates more precipitation than normal. The composite fields of the 8-phase of the 30–60-day filtered 850-hPa zonal wind in the weak summer monsoon years exhibit clearly how the easterly and westerly CISO propagate to the Yangtze River Basin to influence the summer rainfall there (Fig.9).

The above results indicate that both the ISM and WNPSM have significant impacts on the precipitation over the Yangtze River Basin. In the period of the Asian-Pacific monsoon onset, the date of ISM onset is two weeks earlier than the beginning of the Meiyu over the Yangtze River Basin; while in the Asian monsoon

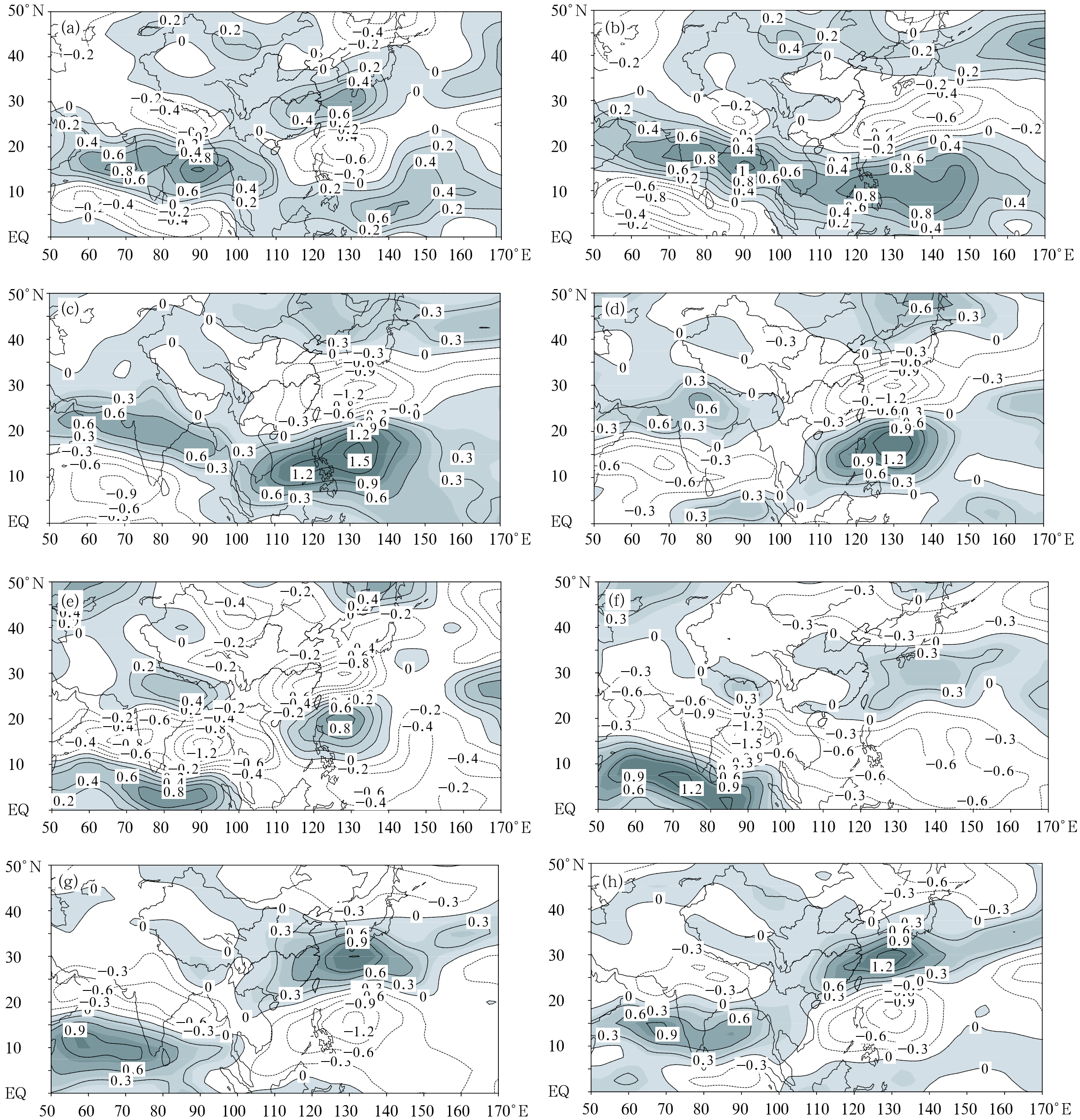

Fig.9. Composite fields of the 8-phase of the 30–60-day filtered 850-hPa zonal wind in summer (Liu and Ding, 2008c). The 30–60-day filtered western wind are shaded, and (a)-(h) denote respectively the 1st–8th phase of CISO.

culmination period, the precipitation of the Yangtze River Basin is influenced significantly by the WNPSM.

4 Teleconnection between WNPSM and the precipitation of northern China

The precipitation in eastern China is mainly influenced by the East Asian summer monsoon (EASM) (Li, 2004; Zhu, 1934; Tu and Huang, 1944), that is, when the EASM is stronger than normal, northern China rainfall becomes more than normal while the Yangtze River Basin rainfall is less. The distribution of the precipitation is opposite in the weak EASM years. The WNPSM and ISM, as the subsystems of the Asian-Pacific monsoon, their intensities are closely correlated to EASM which also belongs to the Asian-Pacific monsoon system, and thus they also impact the precipitation in eastern China. In the preceding two sections, we discussed the teleconnections between the precipitation over the Yangtze River Basin and them, and now we will investigate the teleconnections between the northern China rainfall and WNPSM in the present and next sections.

4.1 Correlation between the northern China rainfall and the WNPSM rainfall

The northern China rainy season mainly is concentrated from mid-July to mid-August every year. We calculate the correlation coefficient between the northern China rainfall (35°–42°N, 112°–122°E) and CMAP of the Asian-Pacific region at the 4th pentad of July to the 3rd pentad of August (Fig.10). It is shown that the precipitation in the east of northern China is in-phase correlated to the western Pacific intertropical convergence zone (ITCZ), and the most significant correlated area lies at 12.5°–20°N, 115°–130°E; while it is out-of-phase correlated to the rainfall over the Yangtze River Basin and the South Japan, the area just under the subtropical high. The correlation between the precipitation of the key area of the western Pacific (12.5°–20°N, 115°–130°E) averaged from the 4th pentad of July to the 3rd pentad of August and the Chinese stations precipitation (Fig. 11) also

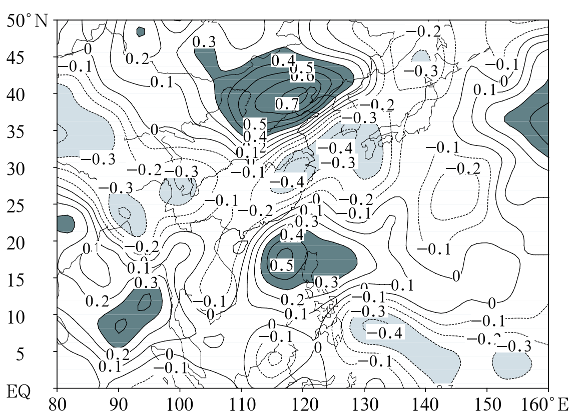

Fig.10. Correlation between the northern China precipitation from the 4th pentad of July to the 3rd pentad of August and CMAP in the Asian-Pacific monsoon region. Correlations at the significant level of α=0.05 are shaded.

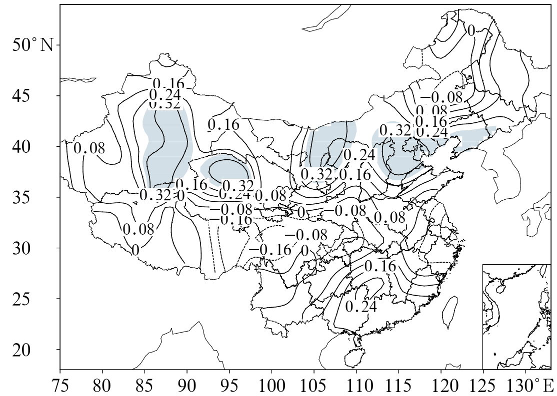

Fig.11. Correlation between the key area of WNPSM from the 4th pentad of July to the 3rd pentad of August and 160 stations precipitation in China. Correlations at the significant level of α=0.05 are shaded.

exhibits the good relationship between the western Pacific rainfall and the northern China rainfall. Besides, the WNPSM rainfall is also in-phase to that of western China and east of Xinjiang, while is out-of-phase to the lower Yangtze River rainfall. Both Figs.10 and 11 are very good descriptions of the significant correlation between the WNPSM rainfall in July and August and the precipitation over the east of northern China.

4.2 Impact of the WNPSM monsoon intensity on the northern China rainfall

The correlation coefficient of the time series of the standardized precipitation in northern China averaged from the 4th pentad of July to the 3rd pentad of August and the precipitation of the key area of WNPSM is 0.53, exceeding the significant level of α=0.05. A comparison of the composite field of atmospheric circulation averaged from the 4th pentad of July to the 3rd pentad of August in the strong and weak WNPSM years can explain clearly the positive correlation between them. Figures 12 and 13 exhibit the 500-hPa geopotential height anomaly and vertical integrated water vapor transport anomaly and divergence anomaly in the strong and weak WNPSM years, respectively. It is shown that in the strong WNPSM years, the anomalous low pressure belt extends from southern China to western Pacific, while the anomalous high lies in northern and northeastern China, Korean Peninsula, and Japan, which indicates that the western Pacific subtropical high (WPSH) tends to be more northeastward abnormally, and the southeasterly current along the southwestern flank of WPSH mainly influences the northern China rainfall. Accordingly, the anomalous tropical westerly water vapor transport combines at about 125°E with the easterly water vapor transport coming from the tropical Pacific, and then turns northward, along the western flank of the anomalously northern WPSH, to the northern and northeastern China, providing abundant water vapor for precipitation there. The related water vapor divergence distribution also indicates that a significant

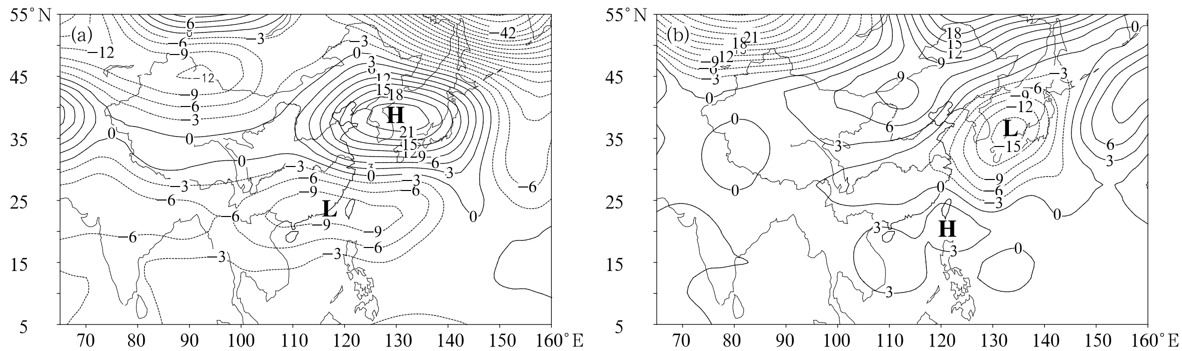

Fig.12. Composite distribution of 500-hPa height anomaly in the strong (a) and weak (b) WNPSM years (unit: gpm).

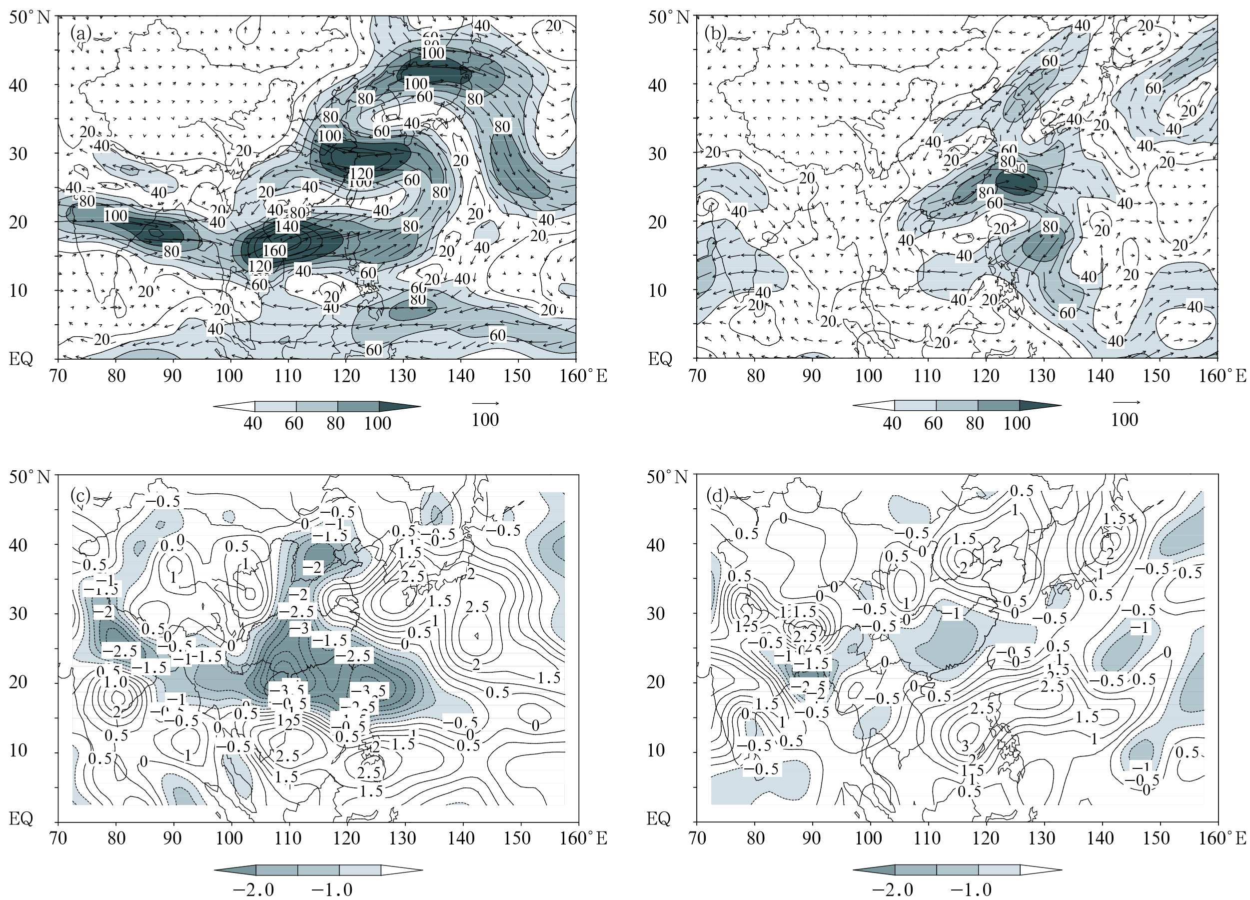

Fig.13. Composite distribution of vertically integrated water vapor transport anomaly (a, b; unit: kg $m^{-1}s^{-1}$) and related divergence anomaly (c, d; unit: 10^{-6} kg $m^{-2}s^{-1}$) in the strong (a, c) and weak (b, d) WNPSM years.

anomalous water vapor convergence area just lies in the southern and northern China, but a water vapor divergence area is in the middle of them, i.e., the middle and lower Yangtze River Basin, corresponding to the drought condition there. However, the situations are completely contrary for the weak WNPSM years. The height anomaly field shows a nearly out-of-phase distribution, indicating that the position of WPSH is abnormally southwestward. The anomalous northerly water vapor transport is exhibited in the high-latitude, illustrating that the southerly water vapor transport derived from the low-latitude is weaker than normal, hard to arrive at northern China, causing much water vapor converged in the Yangtze River Basin. Correspondingly, the anomalous water vapor convergence belt is formed in the Yangtze River Basin, while the anomalous divergence area is in northern China, just explaining the feature of reduced rainfall in northern China in the weak monsoon years.

5. Teleconnection between ISM and the northern China rainfall

5.1 Correlation between ISM and the northern China rainfall

The impact of ISM on the northern China rainfall has already drawn much attention from meteorologists. In the 1980s, existence of the positive correlation in summer rainfall between India and northern China has been discovered by domestic meteorologists, and also been confirmed by some researches at home and abroad (Guo et al., 1988, 1992; Liang, 1988; Kripalani and Kulkarni, 1997, 2001; Liu and Ding, 2008b). Zhang (2001) pointed out that the intensity of ISM has a very important role for the rainfall anomaly in northern China, through the water vapor transport of the ISM to change the water vapor transport in northern China. In the present section, we choose the whole Indian precipitation averaged from June to September to characterize the intensity of ISM, and calculate its correlation with the 160 stations rainfall in China. The result indicates that the ISM has an in-phase relationship with the northern China rainfall, but an out-of-phase relationship with the precipitation in the eastern Tibetan Plateau (seen Fig.1a of Liu and Ding (2008b)). Considering the correlation between the whole Indian precipitation and the CMAP in the Asian monsoon region (seen in Fig.1b of Liu and Ding (2008b)), the southwest-northeastward teleconnection is exhibited from the west of India crossing the Tibetan Plateau to northern China. Comparing it with the teleconnection that relates the precipitation over the Yangtze River Basin depicted in Section 2, we find that the influencing approach of ISM on the East China rainfall in the ISM culmination period is totally different from that in the ISM onset period. The teleconnection from the west of India crossing the Tibetan Plateau to northern China is defined as the "northern" teleconnection, forming in the peak period of ISM, while the teleconnection from the southwest of India crossing BOB to the Yangtze River Basin and South Japan is called the "southern" teleconnection, forming in the ISM onset period (Fig.14). Figure 14 also depicts the CGT wave train found by Ding and Wang (2005). The CGT lies in the mid-latitude westerly belt, but the interactions between ISM and it yet exist in mid-summer. The confluence of the CGT and the "southern" teleconnection at southern Japan and then their downstream propagation together, indicates that the occurrence and maintenance of EASM are influenced not only by ISM from the tropic, but also by the teleconnection wave train from the mid-latitude westerly belt.

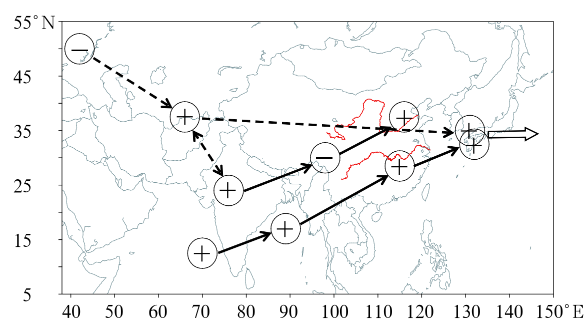

Fig.14. Teleconnections in the Asian-Pacific monsoon region (Liu and Ding, 2008a). The solid lines denote the "northern" and "southern" teleconnections, and the dotted line denotes the CGT wave train (Ding and Wang, 2005).

5.2 Features of the circulation anomalies in the strong and weak monsoon years

ISM anomaly is usually accompanied with the corresponding variations of the atmospheric circulation system in the whole troposphere. Remarkable differences of the atmospheric circulation can be seen from the composite distribution of the circulation systems in the strong and weak ISM years (seen in Fig.5 of Liu and Ding (2008b)). In the strong ISM years, the anomalous sea surface pressure distribution indicates clearly the feature of the monsoon anomaly. Indian low center is stronger than normal, with an obvious eastward and northward extension. Meanwhile, there exists a large anomalous low trough at the mid and high latitude. The interaction between them leads to more than normal precipitation in northern China. The Tibetan Plateau, in the middle of the two low systems, is the relatively high belt, explaining the reduced rainfall in the east of the Tibetan Plateau. The western Pacific is under the control of the subtropical high, with the high ridge's westward extension. The southeasterly monsoon along the southwest flank of the subtropical high brings plenty water vapor to the northern China. Enhancing of the Indian low and the southwesterly monsoon along the southeast flank of the low brings excessive rainfall in the Indian Peninsula. As to the northern China rainfall, it is affected both by the low latitude monsoon, and to a large extent simultaneously by the low pressure circulation in the high latitude, and the above circulation variations cause more rainfall there than normal. Similarly, corresponding changes are found in the mid- and upper-level circulation systems. Both the mid-latitude trough and ridge are strengthened and the subtropical high is farther northward, forming in the height field a pattern of "higher in east and lower in west", favorable for rainfall in northern China. At the 200-hPa anomalous wind field, the southwest-northeast distribution of the anomalous centers is reflected in the pattern of anticyclone, cyclone and anticyclone in sequence, with the South Asian high enhancing. Oppositely, the circulation systems tend to be weaker than normal in the weak ISM years. India and Mongolia are under the control of the anomalous high pressure belt, while western North Pacific is controlled by the anomalous low pressure circulation. Such a circulation setting is disadvantageous to the precipitation in northern China indeed.

In order to reveal more clearly the interaction between ISM and the northern China precipitation, Liu and Ding (2008b) also made a numerical simulation using the high-resolution regional climate model improved by National Climate Center (RegCM-NCC) (figure omitted), and the results also bear out the in-phase correlation between ISM and the precipitation of northern China.

It is indicated from the above analysis that though India and northern China are in different latitude zones, they can display in-phase teleconnection interactions through the role of atmospheric circulation. The Indian low usually impacts on the strength of ISM. When the Indian low deepens, the low trough in mid-high latitude is also strengthened, meanwhile, with the northwestward extension of the WPSH. Such a circulation variation is favorable for more rainfall in northern China than normal, and vice versa.

6. Conclusions and discussion

In the present analysis and review, four different teleconnections in the Asian-Pacific monsoon region have been discussed, which reveal clearly the interactions among the ISM, EASM and WNPSM. As to these findings, we further explain the existence of the teleconnections from the aspects of atmospheric circulation, water vapor transport, numerical simulation, etc.

In the period of the Asian monsoon onset, the date of ISM onset is two weeks earlier than the beginning of the Meiyu over the Yangtze River Basin, and the teleconnection mode sets up from the southwestern India via the BOB to the Yangtze River Basin and southern Japan, i.e. the "southern" teleconnection of the Asian summer monsoon. In the Asian monsoon culmination period, however, the precipitation of the Yangtze River Basin is influenced significantly by WNPSM, and is negatively related to the WNPSM rainfall, that is, when the WNPSM is weaker than normal, the precipitation of the Yangtze River Basin is more than normal. It is found that from the climatological intraseasonal angle, the Yangtze River rainfall is influenced simultaneously by the westerly CISO from the tropical West Pacific and the easterly CISO from the tropical Indian Ocean altogether in the period of the weak WNPSM, forming probably certain phase-locking relationships, giving rise to more rainfall than normal there. In contrast with the rainfall over the Yangtze River Basin, the precipitation of northern China (from the 4th pentad of July to the 3rd pentad of August) is positively related to WNPSM. When WNPSM is stronger than normal, the position of the western Pacific subtropical high (WPSH) becomes farther northeastern than normal, and the anomalous northeastward water vapor transport along the southwestern flank of WPSH is converging over northern China, providing adequate moisture for more rainfall than normal there. The summer rainfall in northern China also has a positive correlation with ISM. During the culmination season of ISM, the teleconnection pattern forms from the northwest of India via the Tibetan Plateau to northern China, i.e., the "northern" teleconnection of the Asian summer monsoon. This is due to the fact that the intensity of ISM is mainly controlled by the Indian low, and when the Indian low deepens, the low trough in the mid-high latitudes is also strengthened with northwestward advance of the northwestern pacific high ridge, which is conducive to the abundant rainfall in northern China.

In the present study, the propagating mechanisms of the four different teleconnections are not investigated. The "southern" and "northern" teleconnections are not located in the westerly jet stream belt, so their formations cannot be explained by so called "the westerly wave train theory". This propagating mechanism should be studied further in the future.

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