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A STUDY ON RESPONSE OF PRECIPITATION IN CHINA TO MONSOON INTRASEASONAL OSCILLATION

YAO Su-xiang (姚素香)[1], HUANG Qian (黄　乾)[1], ZHANG Yao-cun (张耀存)[2], KUANG Xue-yuan (况雪源)[2]

(1. Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science &Technology, Nanjing 210044 China; 2. School of Atmospheric Sciences, Nanjing University, Nanjing 210093 China)

Abstract: Temporal and spatial evolution characteristics of the 30-60 day oscillation (intraseasonal oscillation, ISO) of summer rainfall in China and the effects of East Asian monsoon on the rainfall ISO are analyzed in this paper. Results show that the annual and decadal variations of the oscillation exist between 1960 and 2008, and the intensity is weakest in the late 1970s and early 1980s. In the typical strong years of the rainfall ISO obtained from empirical orthogonal functions (EOF mode 1), an anticyclone is in northwestern Pacific and a cyclone is in the east of China. In the typical weak years, the wind ISO is much weaker. The low-frequency zonal wind and water vapor transport from the low latitudes to mid-latitudes in the typical strong years, and the oscillation strength of diabatic heating is much stronger than that in the weak years of the rainfall ISO. The anomaly characteristics of the rainfall ISO show anti-phases between the Yangtze River basin and south of China. As for the typical strong years of the rainfall ISO in the Yangtze River basin (EOF mode 2), the main oscillation center of water vapor is in the east of China (20–30°N, 110–130°E). In the peak (break) phase of the rainfall oscillation, a low-frequency cyclone (anticyclone) is in the Yangtze River basin and an anticyclone (cyclone) is near Taiwan Island. In addition, the peak rainfall corresponds to the heat source in the Yangtze River basin and the heat sink in the Qinghai-Tibet Plateau. As for the typical strong years of the rainfall ISO in the south of China, the main oscillation center of water vapor is south of 20°N. In the peak (break) phase of the rainfall ISO, a low-frequency cyclone (anticyclone) is in the south of China and an anticyclone (cyclone) is in the Philippines. The peak rainfall corresponds to the heat source in the south of China and the South China Sea, and the heat sink in the west of Indochina.

Key words: precipitation; monsoon; 30-60 day oscillation

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1 INTRODUCTION

Floods are one of the major natural disasters in the joining area of Asia and Indo-Pacific Ocean. Catastrophic floods have caused enormous economic loss and casualties in recent years. In China, floods mainly occur in the Yangtze River basin, the southeast coast and the Huanghuai plain[1-3]. Studies on the rainfall climatic characteristics have shown that, in addition to seasonal changes, the time series of rainfall in the east of China mainly present the intraseasonal oscillation (ISO) characteristics, and the oscillation cycle of the rainfall in the east of China is 30-60 days[4-5].

Researches indicate that not only the power spectrum of some meteorological elements is characterized by the 30-60 day ISO, but also the evolution of atmospheric circulation shows the characteristics of ISO in the summer monsoon region (60–90°E[6-10]). Han et al.[11] analyzed the climatic characteristics of the intraseasonal oscillation in the boreal subtropics, and results show that the ISOs in subtropical regions have significant decadal variations. The study also shows that in East Asia, there is a clear meridional wave train in China's coastal regions. In addition, in the East Asian summer monsoon area, there are distinct longitudinal low-frequency oscillations[12-14]. Studies on the main features of the East Asian summer monsoon ISO indicate that the main oscillation cycle is 30-60 days, and in the coastal areas, the wave train is responsible for the anti-phase relationship between tropical regions and sub-tropical regions in East Asia[9].

Recent researches indicate that the modulation of

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Biography: YAO Su-xiang, associate professor, primarily undertaking research on regional climate and its simulation.
Corresponding author: YAO Su-xiang, e-mail: yaosx@nuist.edu.cn

the East Asian summer monsoon ISO on the rainfall is very important[6, 15-18]. The atmospheric ISOs have important impacts on East Asian monsoon and China's climate, and there is an obvious link between the precipitation in the north of China and the 30-60 day oscillation of the atmosphere. In the flood years, the rainfall 30-60 day oscillation is strong, and in the arid years, the oscillation is not clear in the north of China[9]. The precipitation in East Asia is not only related to the tropical monsoon ISO, but also related to the sub-tropical monsoon ISO, and the zonal and meridional propagation of ISO has impacts on the precipitation[19].

In summary, the precipitation in China has the obvious 30-60 day oscillation, and it is clearly reflected in the meteorological elements and the atmospheric circulation. However, study on the impact of the monsoon ISOs on the spatial and temporal distribution of the precipitation ISOs is insufficient. Therefore, it is necessary to study the 30-60 day oscillation of precipitation in China and the impact of the summer monsoon on the precipitation oscillation. In this paper, the 30-60 day oscillations of summer rainfall in China and the modulation of East Asian monsoon on the rainfall ISOs are analyzed.

2 DATA AND METHODOLOGY

Daily station rainfall data in China and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR, USA) reanalysis data (zonal wind, meridional wind, air temperature, vertical speed, humidity) from 1960 to 2008 were used in this study. First, a Butterworth band-pass filter was used for the rainfall data and the circulation fields (e.g. meridional wind, zonal wind) from April 1 to September 31 (183 days for each year). The mean square deviation (sample length is 183 days) was calculated as the oscillation intensity. Then, the temporal and spatial distributions of the rainfall 30-60 day oscillation intensity were analyzed by the method of empirical orthogonal function (EOF) decomposition. Finally, the typical strong and weak years of rainfall ISOs were selected from 1960 to 2008, and the monsoon ISOs were analyzed for these typical years.

The formula of the vapor transport is as follows:

$$Q = \frac{1}{g}\int_{p}^{p_s} \vec{V} q dp . \quad (1)$$

Here, $\vec{V}$ is the wind speed, q the specific humidity, g the acceleration of gravity, p the top pressure, and p_s the surface pressure.

In addition, the diabatic heating was diagnosed using the first law of thermodynamics, which can be expressed as

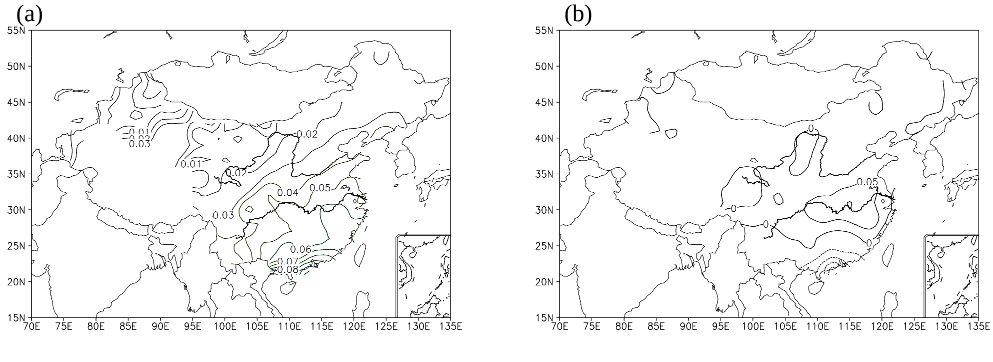
$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \nabla T - \omega\left(\frac{\partial T}{\partial p} - \frac{R}{C_p}\frac{T}{P}\right) + \frac{Q}{C_p} . \quad (2)$$

The local changes of temperature ($\frac{\partial T}{\partial t}$) are determined by the advection of temperature ($-\vec{V} \cdot \nabla T$), vertical transport ($-\omega(\frac{\partial T}{\partial p} - \frac{R}{C_p}\frac{T}{P})$), and diabatic heating ($\frac{Q}{C_p}$).

3 RESULTS

3.1 *The temporal and spatial distribution of the rainfall ISOs*

The first mode and second mode of EOF analysis of the rainfall 30-60 day oscillation strength are analyzed (Figure 1). The variance contribution of the first EOF mode is 83%, and the contribution of the second mode is 6%. The first mode reflects the distribution of mean rainfall oscillation strength (Figure 1a), and the ISOs in the south of China and the Yangtze River basin are more significant than in other areas. The time coefficients of the first mode (Figure 1c) show the annual and decadal variations of the ISO strength. In the 1960s and 1990s, the oscillation is stronger than that in the late 1970s and early 1980s. The study of Han et al.[11] indicates that the meridional wind ISO activities over the subtropical northwestern Pacific are moderate during 1958–1975, weak during 1976–1990, and robust during 1991–2000. Therefore, the decadal variations of the precipitation ISOs are consistent with the meridional wind ISOs.



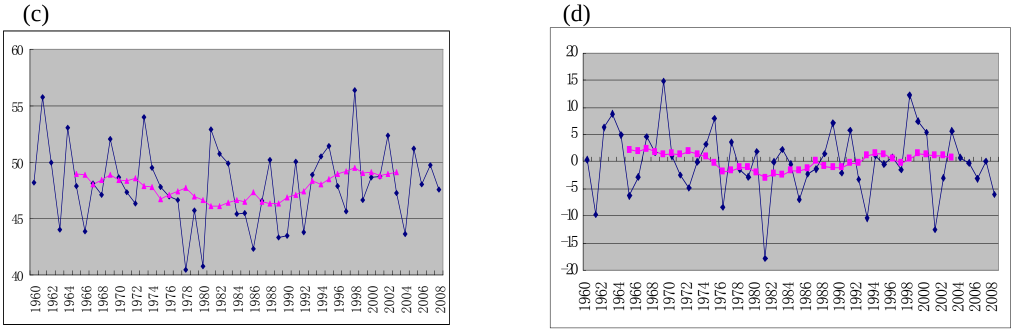


Figure 1. The first mode (spatial distribution, a; time coefficients, c) and the second mode (spatial distribution, b; time coefficients, d) of EOF decomposition of the rainfall ISO strength from 1960 to 2008.

The second EOF mode reflects the oscillation anomaly characteristics (Figure1 b). In the middle of the 1960s and at the end of 1990s, the rainfall oscillation anomaly is positive in the Yangtze River basin and negative in the south of China. From the mid-1970s to the mid-1980s, the rainfall oscillation anomaly is negative in the Yangtze River basin and positive in the south of China. Thus, the relationship of the rainfall 30-60 day oscillation between the south of China and the Yangtze River basin is anti-phase.

3.2 *The impacts of monsoon on the rainfall ISOs*

Based on the above analysis, the typical strong years and weak years of the rainfall ISOs are chosen for further research. As for the first EOF mode of the rainfall ISO strength, the five years with the maximum (minimum) time coefficients are chosen as the typical strong (weak) years in East Asia. Similarly, as for the second EOF mode, the five years with the maximum (minimum) time coefficients are selected (Table 1). Precipitation is closely related to the monsoon wind fields, monsoon vapor transport and diabatic heating, and the characteristics of the wind, vapor transport and diabatic heating will be discussed in the following sections.

Table 1. The typical years of the rainfall oscillation.

	The first mode	The second mode
Strong years	1961, 1964, 1973, 1981, 1998	1963, 1969, 1975, 1989, 1998
Weak years	1978, 1980, 1986, 1989, 1990	1961, 1976, 1981, 1993, 2001

3.2.1 Intensity variations

The anomalies of 850 hPa wind oscillation (30-60 day) in typical strong and weak years are analyzed (Figure 2). In the strong years of the precipitation ISOs in the east of China, the zonal wind ISO strength south of 20°N is stronger than that in the weak years (Figures 2a and 2b). In the land of eastern China, the zonal wind oscillation is also clear. In the typical weak years (Figure 2b), the center of zonal wind oscillation is located in the land north of 30°N. The analysis of the meridional wind oscillations (Figures 2c and 2d) indicates that in the typical strong years of the rainfall ISO, the meridional wind oscillation centers are located in the Bay of Bengal, Indochina, the south of China, the Yangtze River basin, and the northeast of China, and the path is from the ocean to the land. However, in the typical weak years, the centers of the meridional wind ISO are mainly located over the oceans. The main moisture sources of the rainfall in East Asia are the oceans in low latitudes, so the wind oscillations in low latitudes have impacts on the oscillations of precipitation, which reflect in the oscillations of both the zonal and the meridional winds. The wind vector field (Figures 2e and 2f) indicates that in the typical strong years of the rainfall ISO, the eastern China is controlled by a low-frequency cyclone, and the ocean between 20°N and 40°N is controlled by a low-frequency anticyclone (Figure 2e); in the typical weak years, the low-frequency anticyclone is far away from the eastern China, which is not conducive to the precipitation (Figure 2f).

The propagation of the oscillation between the low latitudes and the high latitudes along 100–120°E is further analyzed. On the one hand, the ISO process in different years has its own phase characteristics, and the simple average could weaken the ISO signals; on the other hand, it is difficult to determine the different phases because the rainfall process is different in different areas. Therefore, as for the typical strong and weak years of the rainfall ISO strength (EOF mode 1), we choose the year of 1998 (Figure 3) as the typical strong year with the maximum time coefficient and 1978 (Figure 4) as the typical weak year with the minimum coefficient.

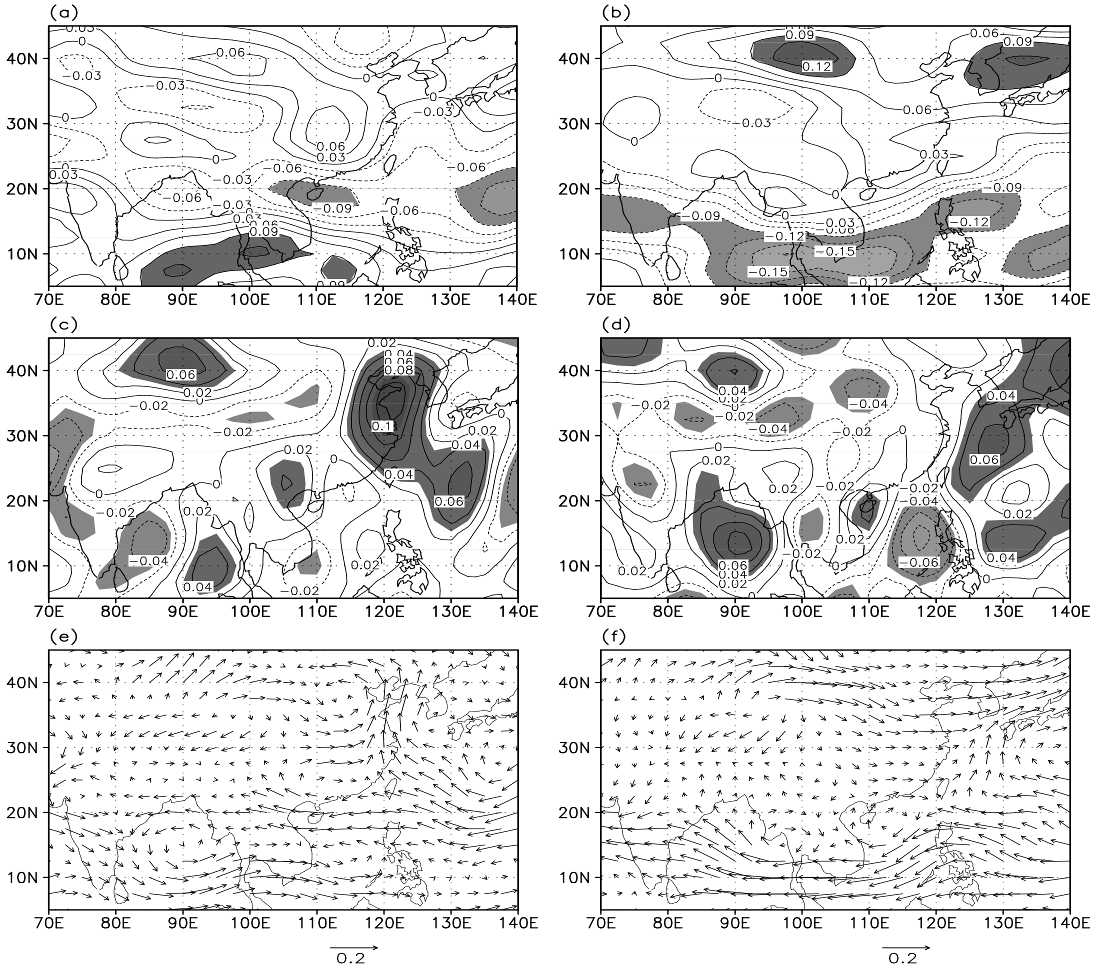


Figure 2. The anomaly of wind ISO in typical years for strong rainfall ISO (zonal wind, a; meridional wind, c; vector, e) and for weak rainfall ISO (zonal wind, b; meridional wind, d; vector, f). Units: m s^{-1}.

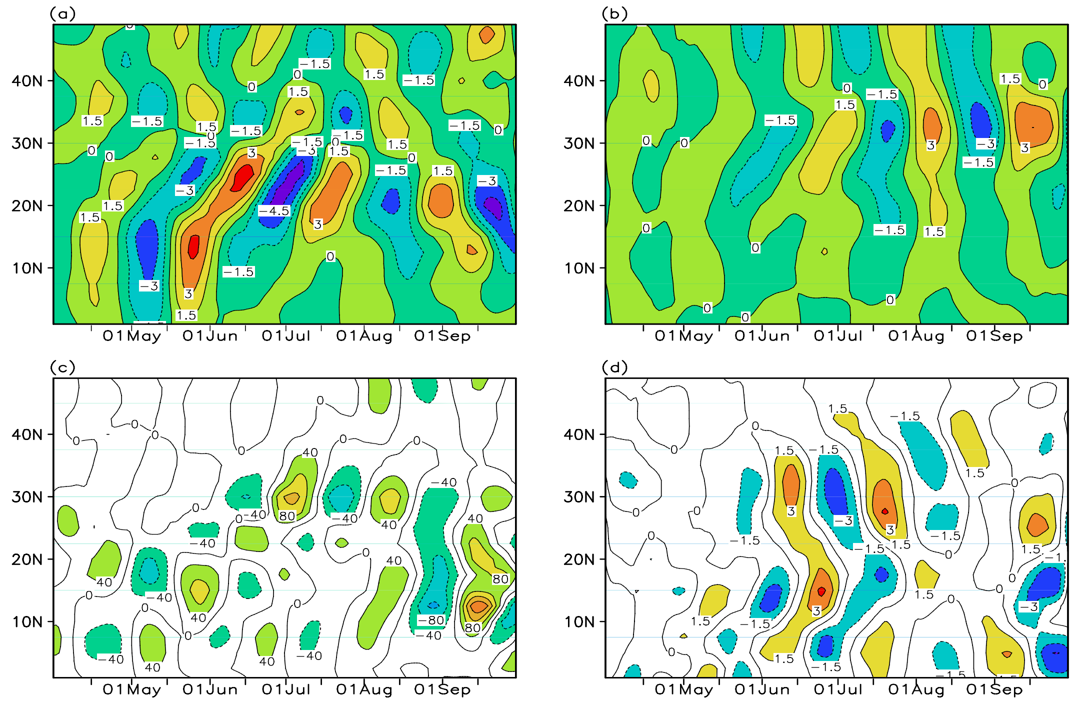


Figure 3. The time-latitude cross section (100-120°E averaged) of low-frequency (30-60 day filter) zonal wind (a, units: m s^{-1}), meridional wind (b, units: m s^{-1}), vapor transport (c, units: kg m^{-1} s^{-1}), and diabatic heating (d, units: °C d^{-1}) in 1998.

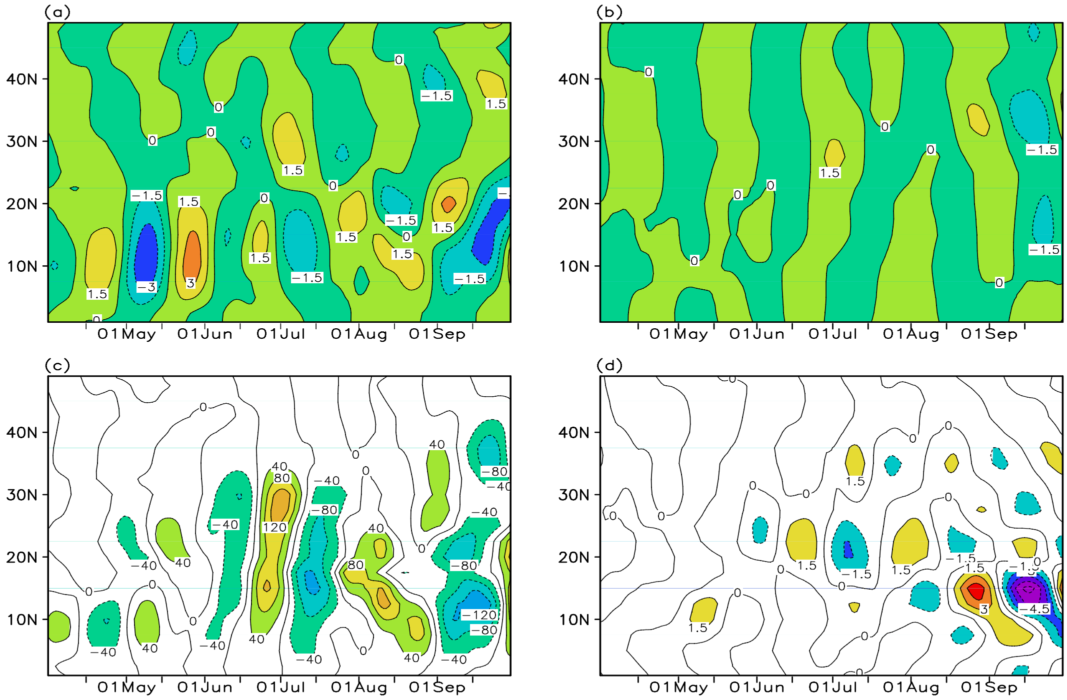


Figure 4. Same as Figure 3 but for 1978.

The time-latitude section of the zonal wind oscillation in 1998 is shown in Figure 3a. There are two zonal wind wave trains in 1998. One of the wave trains propagates from the low latitudes to the middle latitudes, and the other one propagates from the high latitudes to the middle latitudes. The zonal wind wave train from low latitudes can spread to the areas north of 30°N in 1998, and the oscillation is stronger than that in 1978 (Figure 4a), especially from July to September. In the weak year of the rainfall ISOs (1978), the zonal wind ISO centers stay in the area south of 20°N. In addition, the wave speed of the zonal wind oscillation in 1998 is slower. The analysis of the meridional wind oscillation indicates that in 1998 (Figure 3b), the meridional wind oscillation is stronger in the areas of 30–40°N than that in 1978 (Figure 4b).

The characteristics of the water vapor (integrated from the surface to 300 hPa) ISOs in 1998 (Figure 3c) and 1978 (Figure 4c) are also analyzed. The water vapor transports from the low latitudes to the area of 30–40°N in 1998, and the ISO maximum centers are located in 30–40°N. The spread characteristics of the water vapor flux from the low latitudes to the middle latitudes in 1978 (Figure 4c) are less significant compared with that in 1998.

The upward motion is closely related to the diabatic heating, so it is necessary to analyze the diabatic heating. The positive diabatic heating indicates the heat source, which is conducive to the precipitation, while the negative diabatic heating represents the heat sink, which corresponds to interruption of the precipitation. As for the low-frequency diabatic heating, the differences between 1998 (Figure 3d) and 1978 (Figure 4d) are also noticeable. In 1998, there are two latitudinal belts (10–20°N and 25–40°N) where the diabatic heating is strong. In 1978, the maximum centers of diatatic heating are between 10°N and 30°N, and the strength is weaker than that in 1998.

3.2.2 IMPACT OF THE MONSOON ON THE RAINFALL ISO ANOMALY DISTRIBUTION

As the second EOF mode of the rainfall 30-60 day oscillation shows an anti-phase relationship between the Yangtze River basin and the south of China, the impact of the monsoon ISO on the rainfall ISO anomaly is further studied in this section. Here, the high coefficients of the second EOF mode indicate the strong rainfall oscillation in the Yangtze River basin, and the low coefficients suggest strong rainfall oscillation in the south of China. The precipitation ISOs in the Yangtze River basin and the south of China are divided into four phases (break phase, transition from break phase to peak phase, peak phase, and transition from peak phase to break phase) in every typical year, and then the low-frequency wind, water vapor, and diabatic heating in the same phase are composed.

As for the typical strong years of the rainfall ISO in the Yangtze River basin (Figures 5 and 6), a low-frequency anticyclone is in the area of 30°N and a cyclone is near Taiwan Island (Figure 5a) in the break phase. Thus, it is divergent near the Yangtze River basin for low-frequency water vapor. In the peak phase, a low-frequency cyclone is in the areas of

30–40°N (the Yangtze River basin and area to its north, Figure 5c), and a low-frequency anticyclone is in northwestern Pacific. Thus, it is convergent between southwest wind and northwest wind, which is conducive to the generation of precipitation. The low-frequency distribution in the transitional phase from the break to the peak (Figure 5b) is opposite to that from the peak to the break (Figure 5d). In the phase from the break to the peak, it is controlled by a low-frequency anticyclone in the South China Sea, and in the phase from the peak to the break, it is controlled by a low-frequency cyclone in the South China Sea.

The low-frequency diabatic heating in different phases of the rainfall ISO is shown in Figure 6. In the break phase of the rainfall oscillation (Figure 6a), the heat sink is over the areas from the Yangtze River basin to the South China Sea, and a heat source is in the south of Qinghai-Tibet Plateau. In the peak phase of rainfall oscillation (Figure 6c), the maximum heat source is in the upper Yangtze River basin. The heat source is over the areas from the Yangtze River basin to the South China Sea, and a heat sink is in the south of Qinghai-Tibet Plateau. In the phase from rainfall break to rainfall peak (Figure 6b), a heat sink is in north of the Yangtze River basin, and a heat source is in the south of the Yangtze River basin, which is opposite to that in the phase from rainfall peak to rainfall break (Figure 6d).

As for the typical strong years of the rainfall ISO in the south of China, the low-frequency water vapor and diabatic heating are also analyzed (Figures 7 and 8). In the rainfall break phase (Figure 7a), a low-frequency anticyclone is in the south of China and a cyclone is in the South China Sea. In the transitional phase from rainfall break to rainfall peak (Figure 7b), there is a low-frequency cyclone in northwestern Pacific. In the rainfall peak phase (Figure 7c), a low-frequency cyclone controls the south of China, and an anticyclone is in the Philippines. In the phase from rainfall peak to break (Figure 7d), the low-frequency anticyclone moves to Taiwan Island.

In the break phase of the rainfall ISO (Figure 8a), a heat source is in Qinghai-Tibet Plateau, and a heat sink is from the south of China to the South China Sea. In the low latitudes, there are some diabatic heating centers. There is a heat sink in the east of Indian Peninsula, a heat source in the west of Indochina, a heat sink in the South China Sea, and a heat source in the Philippines. The pattern in the rainfall peak phase (Figure 8c) is opposite to that in the break phase, especially in the low latitudes. In the transitional phase from rainfall break to rainfall peak (Figure 8b), a low-frequency heat source is in the southeast of China, and a heat sink is in the South China Sea, which is conducive to the generation of the precipitation in the south of China. In the transitional phase from the rainfall peak to break (Figure 8d), a low-frequency heat sink is in the south of China and a heat source is in the South China Sea, and the precipitation decreases in the south of China.

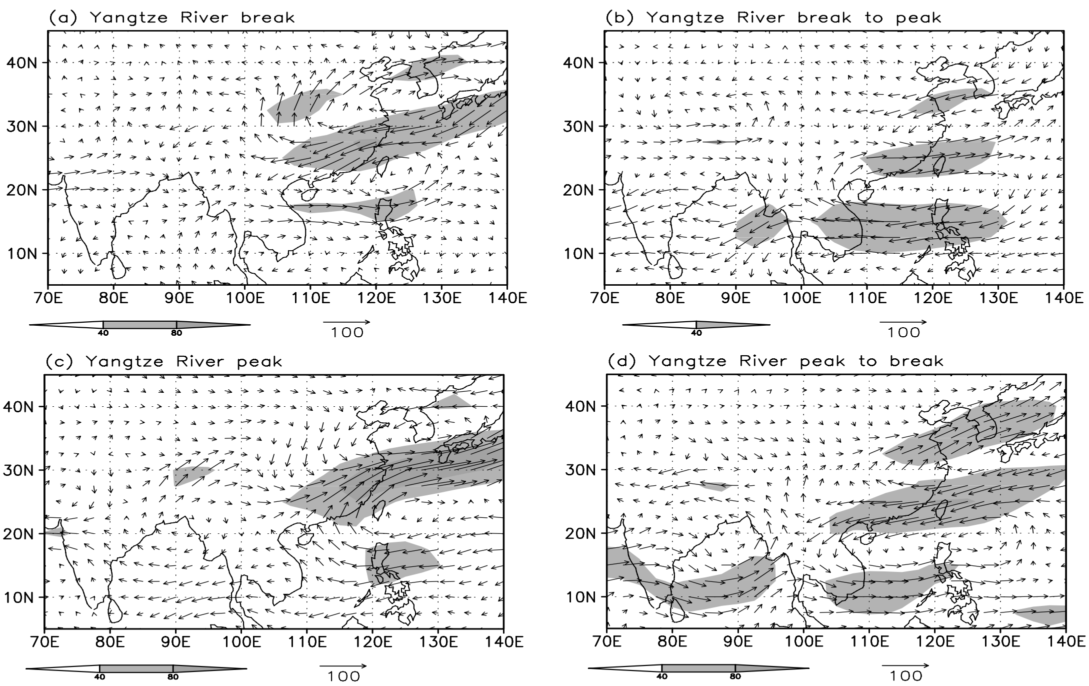


Figure 5. Low-frequency water vapor transport in different rainfall ISO phases (break, a; the conversion from break to peak, b; peak, c; the conversion from peak to break, d) in typical strong years over the Yangtze River basin (shaded areas indicate values exceeding 40 kg m^{-1} s^{-1}. Units: kg m^{-1} s^{-1}).

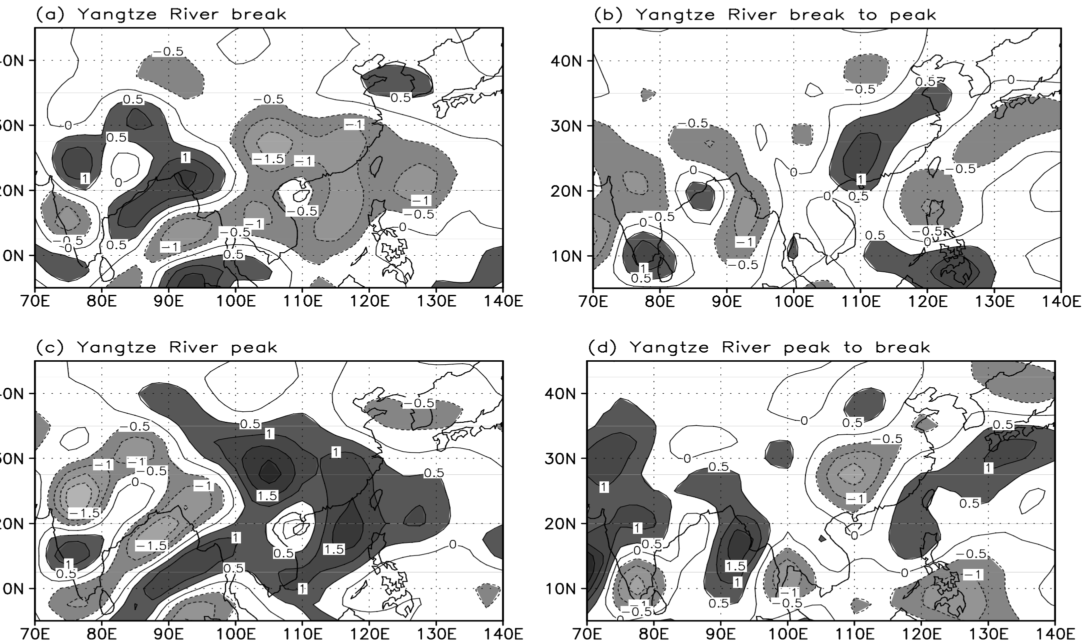


Figure 6. The same as Figure 5 but for low-frequency diabatic heating (Unit: °C d^{-1}).

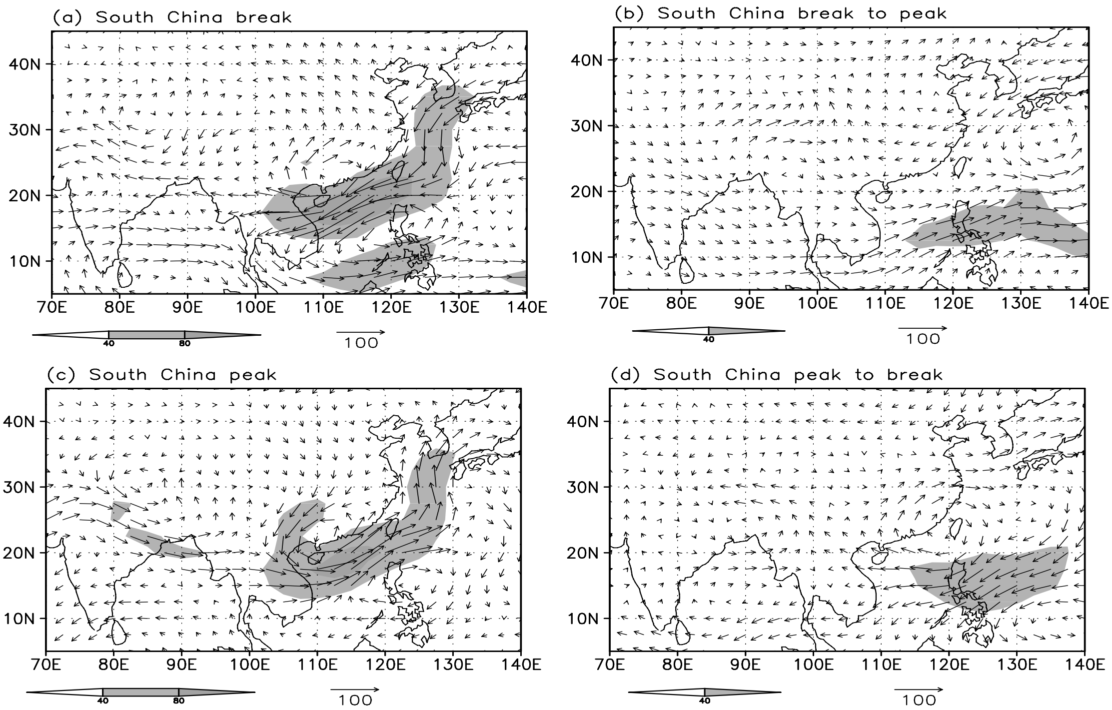


Figure 7. Low-frequency water vapor transport in different rainfall ISO phases (break, a; the transition from break to peak, b; peak, c; the transition from peak to break, d) in typical strong years over South China (shaded areas indicate values exceeding 40 kg m^{-1} s^{-1}. Units: kg m^{-1} s^{-1}).

4 CONCLUSIONS AND DISCUSSION

In summary, the rainfall ISO centers are located in the south of China and the Yangtze River basin, and there are annual and decadal variations in the oscillation between 1960 and 2008. The intensity of the rainfall oscillation in China is weakest in the late 1970s and early 1980s. The anomalies of rainfall oscillation exhibit an anti-phase relationship between the Yangtze River basin and the south of China.

In the typical strong years of rainfall ISO (EOF mode 1), an anticyclone is in northwestern Pacific and a cyclone is in the east of China. In the typical weak years, the wind ISO is much weaker. In the typical strong years, the low-frequency zonal wind and water vapor transport from low latitudes to mid-latitudes, and the oscillation of diabatic heating is much stronger than that in weak years of the rainfall ISO.

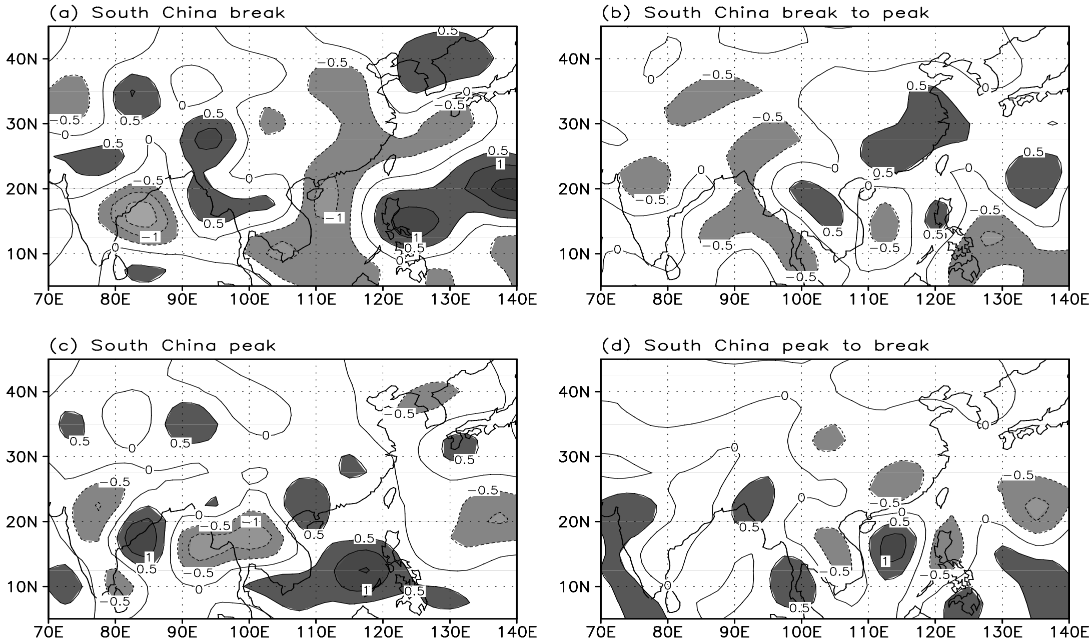


Figure 8. The same as Figure 7, but for low-frequency diabatic heating (Unit: °Cd^{-1}).

As for the typical strong years of the rainfall ISO in the Yangtze River basin (EOF mode 2), the main oscillation center of water vapor is in the east of China (20–30°N, 110–130°E). In the peak (break) phase of the rainfall oscillation, a low-frequency cyclone (anticyclone) is in the Yangtze River basin and an anticyclone (cyclone) is near Taiwan Island. In addition, the peak rainfall corresponds to the heat source in the Yangtze River basin and the heat sink in the Qinghai-Tibet Plateau.

As for the typical strong years of the rainfall ISO in the south of China, the main oscillation center of water vapor is south of 20°N. In the peak (break) phase of the rainfall ISO, a low-frequency cyclone (anticyclone) is in the south of China and an anticyclone (cyclone) is in the Philippines. The peak rainfall corresponds to the heat source in the south of China and the South China Sea and the heat sink in the west of Indochina.

It is noteworthy that the results about the relationship between the precipitation ISOs and propagation of the monsoon ISOs are somewhat preliminary. What is the main impact factor on the propagation of monsoon ISOs? What is the relationship between the monsoon strength and the meridional propagation of ISOs? These issues must be resolved and are also the focus of future study.

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