Climatic characteristics of the Jianghuai cyclone and its linkage with precipitation during the Meiyu period from 1961 to 2020

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Abstract. This study examines the climatic characteristics of 202 Jianghuai cyclones and their linkage with precipitation during the Meiyu period from 1961 to 2020. The results show that cyclones mainly originate from eastern Hubei Province and south-central Anhui Province, and further explored the statistical characteristics of the strength, radius, and their positive correlation. When studying the interdecadal variation of cyclones, we found that there is a similar trend between the interdecadal variation of cyclones and Meiyu precipitation. Therefore, we further investigate the correlation between the Jianghuai cyclones and the precipitation during the Meiyu period. There is a positive correlation coefficient of 0.769 between them. It's worth mentioning that the percentage of precipitation affected by cyclone activities can reach up to 47%. The anomalous increase in precipitation caused by cyclones above 27°N can reach a maximum of 7 mm/day. When the cyclone existed, there was a significant altitude anomaly of negative geopotential height can be traced to day -4 at the 500 hPa level over Mongolia. The abnormally enhanced WPSH, southwest jet and negative geopotential height are the dominant factors causing abnormal precipitation during Jianghuai cyclones. Before and after the cyclone developed, water vapor flux and divergence from low latitudes abnormally increased. These provide sufficient water vapor conditions for the generation of cyclone precipitation.

1. Introduction

Meiyu is a special rainy season due to the progress of the East Asian summer monsoon. The East Asian summer monsoon broke out in the South China Sea in mid-May and then advanced northward, forming rain bands in South China, the Jianghuai region, the Korean Peninsula and Japan (Ding et al., 2004,2007; Qian et al., 2000). The name for this special rainy season is called Meiyu in China, while it is called Changma in South Korea and it is called Baiu in Japan (Ninomiya et al., 1987; Oh et al., 1997; Saito. 1995;). Meiyu front is one of the important weather systems affecting summer precipitation in the middle and lower reaches of the Yangtze River (Pang et al., 2013; Wang et al., 2014; Zhou et al., 2022; Tao et al., 1979). From mid-June to early July, the east of Yichang, Hubei Province, has continuous rains and short sunshine. These conditions are accompanied by heavy rainfall, strong wind and other weather phenomena in these areas during the Meiyu period (Ding. 1992; Zhao et al., 2021; Zhou et al., 2017). In China, the mean annual precipitation during the Meiyu period in the Jianghuai River Basin can reach 300 mm, accounting for 30%-40% of the mean annual total precipitation, and even up to 500 mm or more in the extreme Meiyu period (Liu et al., 2020). Historically, most of the summer floods disasters are caused by precipitation anomalies in the Meiyu period. Some scholars have studied and analyzed the representative floods of 1996, 1998, 2016 and 2020 (Bao et al., 2021; Su et al., 2021; Zhao et al., 2018; Zhong et al., 2023). These floods, caused by the Meiyu front, had adverse effects on people’s safety, lives and property (Yan et al., 2021). Scholars in China have divided rainstorms caused by Meiyu fronts into three types (Zhang et al., 2004). The first type is the β mesoscale convective rainstorm on the Meiyu front. This type of rainstorm has a range of less than 300 km with strong intensity and a fast formation process (He et al., 2007). It is difficult to forecast before 12 hours and can be detected only by using radar to make a proximity forecast (Zhang et al., 2002). The second type is the persistent rainstorm located in front of the high-altitude low-pressure tank in the western part of the Meiyu front. It is characterized by a long duration of approximately 5 days but appears less frequently, mainly in western Hubei and western

Hunan and Sichuan (Cai et al., 2021; Wu et al., 2020;). The last type is the rainstorm caused by the Jianghuai cyclone located east of the origin of the Meiyu. The Jianghuai cyclones are affected by the thermal conditions of the sea and land and likely occur in the eastern part of the Meiyu front (Wang et al., 2016). The positive vorticity advection in front of the high-altitude trough and the warm advection in front of the front promote the eastward movement and development of the cyclone (Shen et al., 2019; Zhang et al., 2016). During the development of the cyclone, the lower levels are dominated by the southwest warm and humid airflow, and the high levels are mainly affected by dry and cold air (Zhao et al., 2008). This type of rainstorm has a large range, high intensity and long duration of precipitation (Wang et al., 2012; Xu et al., 2011).

Scholars' studies on Jianghuai cyclones during the Meiyu period were initially based on individual case analysis. Xu et al. (2013) studied a cyclone process in 2011 and found that the cyclone process lasted up to 36 h. The cyclone rainstorm was distributed on the south side of the cyclone. Heavy precipitation during the whole cyclone mainly occurred in the lower reaches of the Yangtze River. Wu et al. (2020) studied 2 different cyclone rainstorm processes. They found that rainfall is directly proportional to cyclone intensity. There is a strong convergence center of water vapor flux during cyclone development. Zhou et al. (2020) found that a tornado was generated from the cyclone occlusion stage on July 22. The tornado was under the influence of a strong and fast Jianghuai cyclone and produced heavy precipitation accompanied by thunderstorm phenomena. With the improvement of cyclone identification methods and reconstruction of reanalysis data, statistical studies of cyclones have been further developed (Simmonds et al., 1999; 2000; Wernli et al., 2006). Yang et al. (2010) modeled the rainstorm process in the lower reaches of the Yangtze River from 1998 to 2005. The cyclones accounted for 62.5% of the rainstorm cases, and more than 70% of the cyclones could develop and produce rainstorms. The Jianghuai cyclone located in the lower reaches of the Yangtze River generally exists in the lower troposphere at 700 hPa. The horizontal scale is within 400 km, and the life period on land is generally less than 48 h. Wang et al. (2015) found that the number of cyclones was lower and their intensity was weak in the 1980s and 1990s. In the early 2000s, cyclones were more frequent, and their intensity increased. After 2010, there was again a decreasing trend. Zhang et al. (2018) divided 60 cases of extreme precipitation in the middle reaches of the Yangtze River from 2008 to 2015 into five types. Among them, the extreme precipitation of the Jianghuai cyclone type accounted for 30%. The stable and maintained Western Pacific subtropical high (WPSH) system is one of the important reasons for the strong precipitation produced by cyclones. Because of the weak cold air force, the intensity of the Jianghuai cyclone is weaker than that in spring (Zhou et al., 2017). The daily analysis of the Jianghuai cyclones in the Meiyu period is easy to ignore. All these studies indicate that the Jianghuai cyclone is an important weather system that causes heavy rainfall during the Meiyu period in the middle and lower reaches of the Yangtze River (Wu et al., 2021; Zhang et al., 2018; Zhu et al., 1998).

Research on the climatic characteristics and precipitation effects of Jianghuai cyclones during the Meiyu period in the past 60 years has not yielded clear results. In this study, the relative vorticity method is used to objectively identify and track cyclones based on reanalysis data provided by ERA5. The climatological characteristics of the Jianghuai cyclones during this period are studied. We analyze the correlation between Jianghuai cyclone activity and precipitation. This study provides a reference for the long-term and short-term forecasting of precipitation in the Meiyu period.

The remainder of the present paper is organized as follows. Section 2 of this paper presents the dataset and analytical methods. In Section 3, we show the climatology composite of the cyclone tracks, genesis locations, intensity, lifetime and so on. There is a positive correlation between the frequency of cyclonic activity and precipitation in the Meiyu period. The relationship between them is studied by means of the geopotential height anomaly and water vapor flux anomaly. Section 4 provides the main discussion and findings of this study.

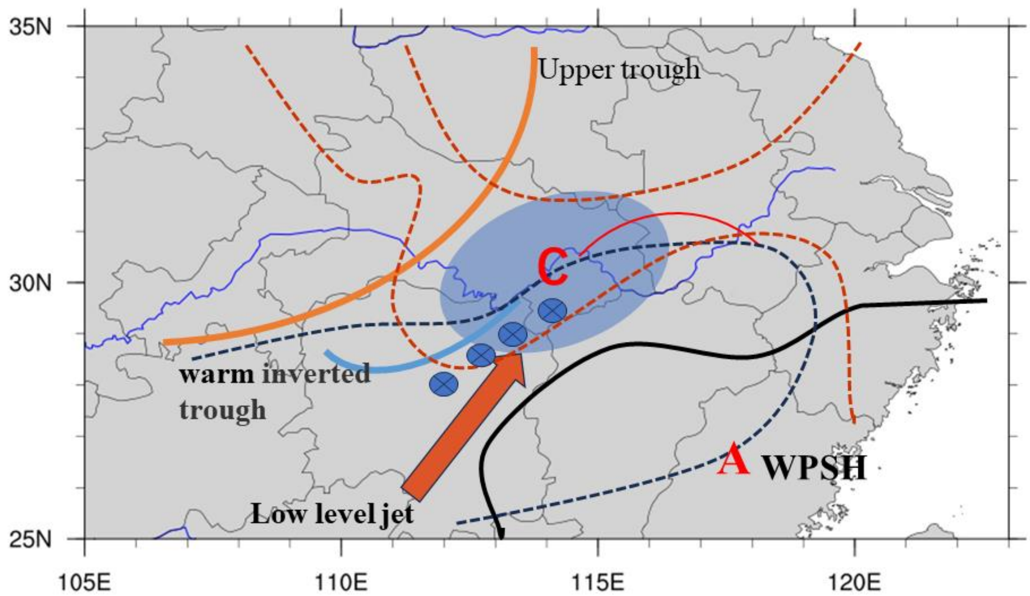

Fig.1 Schematic diagram of the main weather system and the structure of temperature and pressure field in the middle and low levels of the Jianghuai cyclone. (Red dotted line: isotherm; Solid black line: contour line; Blue dot: precipitation area; Solid orange line: 500 hPa upper-level trough; Red arrow: low level jet; Black dotted line: warm inverted trough; Solid red line: warm shear; Solid blue line: cold shear; Letter C: cyclone; Letter A: WSPH.)

2. Data and methods

2.1 Data

The time span of all the data is 60 years from 1961 to 2020, and the study area is located at 108°E-123°E, 27°N-34°N. We use the ERA5 relative vorticity hourly data (850 hPa) released by the European Centre for Medium Range Weather Forecasts (ECMWF) for Jianghuai cyclone identification and tracking. The spatial resolution of the data is 0.25°×0.25°, and the temporal resolution is 6 h. Every 6 h was defined as a step. The data of geopotential height, wind field, and specific humidity are daily data processed from ERA5 hourly data with a spatial resolution of 0.25°×0.25° (Hersbach et al., 2018). The geopotential height and wind field data include pressure levels of approximately 500 hPa, 700 hPa and 850 hPa. The specific humidity data include pressure levels of approximately 500 hPa, 700 hPa and 850 hPa. The precipitation data are from the CN05.1 grid point observation dataset compiled by the National Meteorological Information Center of China Meteorological Administration with a resolution of 0.25°×0.25°.

We used the Meiyu intensity index to characterize the strength of Meiyu, and data is from the National Climate Center of China. The Meiyu intensity index is defined as:

$$M = \frac{L}{L_0} + \frac{0.5(R/L)}{R_0/L_0} + \frac{R}{R_0} - 2.5$$

M is the Meiyu intensity index. L is the length of the Meiyu in a given year (unit: day) and L_0 means the average length of the Meiyu over the years (units: day). R is the total precipitation of Jianghuai River basin during Meiyu in a given year, and R_0 is the average total precipitation of Jianghuai River basin during Meiyu over the years. The average period is from 1961 to the current year. For example, L_0 and R_0 values for 2000 are the averages from 1961 to 2000. Where M between -0.375 and 0.375, China Meteorological Administration defines this year as the normal. Where M between 0.375 and1.25, this year is defined as a little strong. Where M greater than or equal to 1.25, this year is defined as strong. Where M between -1.25 and -0.375, this year is defined as a little weak. Where M less than or equal to -1.25, this year is defined as weak (GB/T 33671-2017).

2.2 Methods

The objective identification and tracking method for cyclones used in this paper is the vorticity tracking method proposed by Hodges (1994, 1995). The first step is to use the relative vorticity field at the 850 hPa pressure level corresponding to every moment of the cyclone to determine the range of each cyclone. The second step is to find the feature points. In the process of finding the feature points, the extreme point and the centroid point are the alternatives. Corresponding to the global relative vorticity grid data of each time point, several feature points can be found, and each point represents a cyclone. The third step is to match the track of each cyclone under the given time span. In Hodges (1994), the assumed data used are defined on a rectangular grid, and each time step is initially processed to identify the maximum or minimum value of the "object" on the positioning grid. The tracking method is feasible on high-resolution grids, but on low-resolution grids, the feature points may not be sufficient to produce smooth trajectories, so the smoothness of the tracking algorithm is effectively limited. Hodges (1995) proposed tracking feature points on the unit sphere, which would become the feature point matching problem of grid data for adjacent time points in cyclone tracking. If the algorithm is reasonable, there is no "discontinuity" mutation in the final arriving cyclone track, and the track is more accurate.

In addition to the relative vorticity method of tracking proposed by Hodges, different methods of cyclone identification have also been proposed by other scholars. Lu (2017) improved the extratropical cyclone identification and tracking method involving the nine-point pressure minimum. Jiang et al. (2020) proposed an algorithm for identifying extratropical cyclones on the basis of gridded data. This algorithm is named the eight-section slope detection method. Among them, the most commonly used cyclone tracking methods are the mean sea level pressure method (SLP) and 850 hPa relative vorticity method. Mailier et.al (2006) and Zhang et.al (2012) studied the tracks of individual cyclones in these two methods. Both of them found 850 hPa relative vorticity method can identify and detect cyclone center earlier than the SLP method (Mailier et al., 2006). The reason for this result is that SLP is easily affected by topography and large-scale background circulation shear vorticity (Hodges, 1994). So based on this advantage of the relative vorticity method, we select the 850 hPa relative vorticity tracking method. The relative vorticity tracking method can detect low vortex systems earlier and track cyclones for a longer period of time with better stability. When the closed pressure levels are not visible on the satellite map, the vorticity tracking method can still continue to track the cyclone, improving the accuracy of cyclone track data.

3. Results

3.1 Climatic characteristics of the Jianghuai cyclone during the Meiyu period

A total of 202 Jianghuai cyclones existed during the Meiyu period from 1961 to 2020. The range of cyclone genesis locations defined by the Jiangsu Meteorological Administration (2017) and the characteristics of the relative vorticity tracking method were used. We adjust the genesis location and remove the cyclones that are generated at sea and have no effect on land precipitation (108°E-123°E, 28°N-35°N). Figure 2a shows the distribution of Jianghuai cyclone tracks. The brown dots represent the genesis locations of the first occurrence of the Jianghuai cyclone. The yellow lines indicate the tracks of the cyclones. As shown in the figure, the tracks of the cyclone are mainly eastward and northeast. These two kinds of tracks are related to the upper-level guide airflow of 500~700 hPa (Wei et al., 2013). The northeast track is mainly due to the southwest warm and moist air on the edge of the WPSH. The east track is mainly related to the location of the WPSH. Figure 2b shows the frequency of cyclone occurrence refers to the total number of cyclones during the Meiyu period from 1961 to 2020.The genesis locations of cyclones are mainly located in the middle and lower reaches of the Yangtze River and the Huaihe River basin, with an east–west band distribution (Wang et al., 2015; Wu et al., 2021). The frequency of occurrence refers to the total number of cyclones during the Meiyu period from 1961 to 2020 is higher in the region of the Hubei and Chongqing junction, eastern Hubei, northern Jiangxi, south-central Anhui, Jiangsu and Zhejiang. Research has found that the genesis locations of cyclones are closely related to the landform (Xu 2021; Zhang et al., 2012).

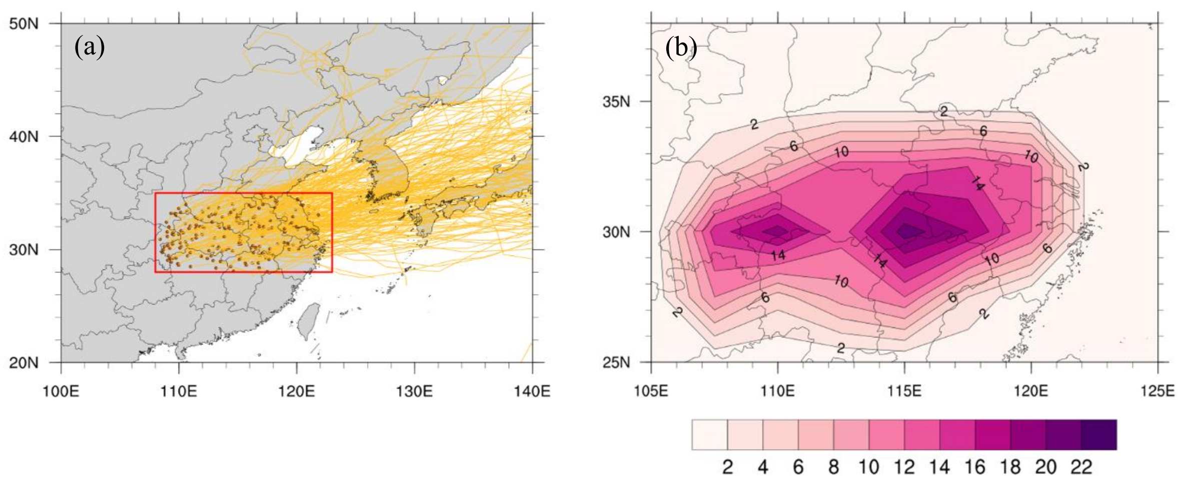

Fig 2. Distribution of the cyclone genesis locations, tracks (a) and the frequency of

genesis locations refers to the total number of cyclones (b) during the Meiyu period from 1961 to 2020 (The brown dots represent the genesis locations. The yellow lines indicate the tracks).

To examine the climatological characteristics of Jianghuai cyclones over 60 years, we focus on the intensity, radius, and lifetime of cyclones on land. The intensity of the Jianghuai cyclone is defined as the relative vorticity intensity of the 850 hPa cyclone center. The larger the relative vorticity intensity is, the stronger the cyclone intensity is. Figure 3a shows that among the 202 selected cyclones, the intensity of the cyclone center mainly ranges from 0×10^{-5} s^{-1} to 7×10^{-5} s^{-1}. When the intensity of the cyclone center is less than 3×10^{-5} s^{-1}, the number of cyclones increases with increasing intensity; when it is larger than 3×10^{-5} s^{-1}, the number of cyclones decreases with weakening intensity. The number of cyclones in the range of 2×10^{-5} s^{-1} to 3×10^{-5} s^{-1} has the largest proportion, accounting for 36% of the total number of cyclones. A total of 180 cyclones are in the range of 1×10^{-5} s^{-1} to 5×10^{-5} s^{-1} in intensity, accounting for 89%. Figure 3b shows the relationship between the radius of cyclones and the number of cyclones. Most of the cyclones have an average radius between 300 and 800 km, accounting for 96% of the total number. The number of cyclones with radii between 500 and 600 km is the largest, accounting for 35%. Figure 3c shows the relationship between the time of cyclones affecting precipitation on land and the number of cyclones. Most of the cyclones affect precipitation on land for 1-3 days, and only one cyclone affects precipitation on land for more than 3 days. The number of cyclones that affected precipitation on land within 2 days was 186, accounting for 92% of the total number.

The intensity of a cyclone is one of the factors affecting its precipitation and impact range during the Meiyu period (Zhao et al., 2010). Figure 4a shows a positive correlation between the maximum intensity and the maximum radius of cyclone development. The stronger the intensity of a cyclone is, the larger its radius. Therefore, the horizontal scale of most strong cyclones is larger than that of weak cyclones, the precipitation is greater, and the precipitation range is larger. From the distribution of difference value of track step between the maximum intensity and the radius of the cyclone shown in Figure 4b, the number of cyclones that reach both at the same time accounts for 45% of the total number of cyclones. Of the remaining Jianghuai cyclones, more reach the maximum intensity first and continue to develop to the maximum horizontal scale.

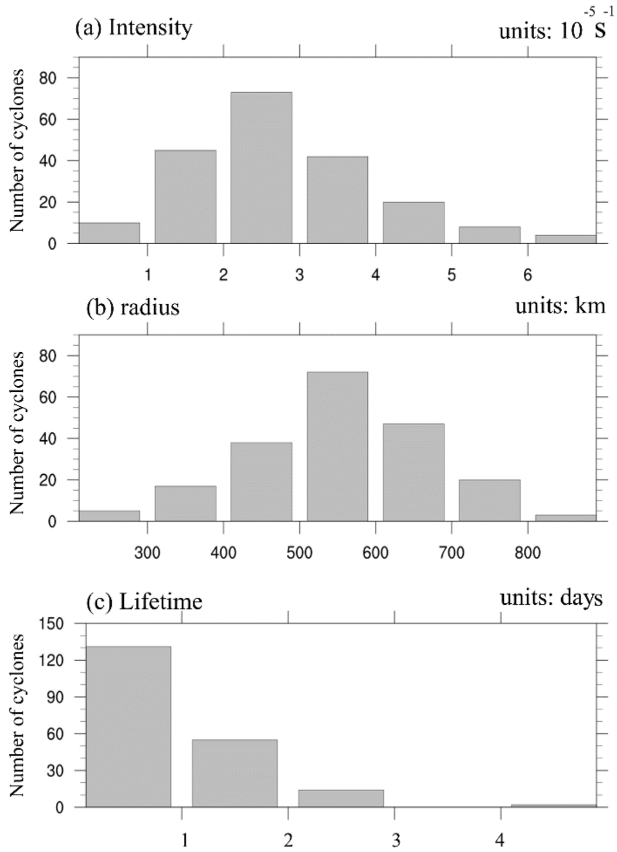

Fig 3. Distributions of the number of selected cyclones versus their (a) intensities (units: $10^{-5}\ s^{-1}$), (b) radii (units: km), and (c) lifetimes (units: days).

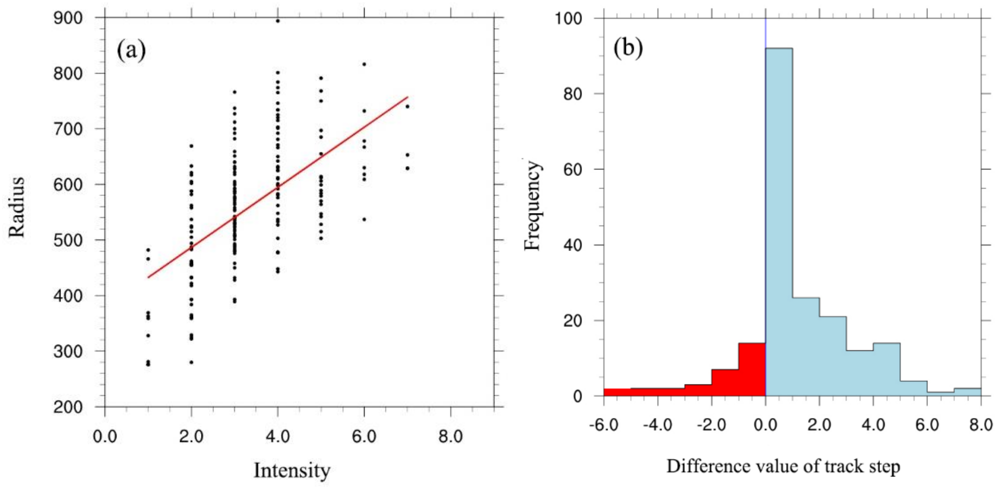

Fig 4. Correlation between maximum intensity (units: 10^{-5} s^{-1}) and maximum radius (units: km) (a) and their difference value of track step during the development of the Jianghuai cyclone in the Meiyu period (b).

The frequency of Jianghuai cyclone occurrence refers to the total number of cyclones is characterized by multiperiod variation (Figure 5). The shaded area in the figure indicates that the 95% confidence interval according to the T test is passed. Strong 2–4-year quasiperiodic variation is observed for 1980-1990 and 1990-2000. After 2000, the quasiperiodic change in cyclones is approximately 4-5 years. This change period corresponds to the period of abnormal change in Meiyu. Chen et al. (2019) pointed out that 3~4 years of quasiperiodic change is the main component of abnormal changes in Meiyu when studying the quasiperiodic change in Meiyu. This quasiperiodic variation component is mainly influenced by the out-of-ocean forcing of the Indian Ocean dipole (IOP), which changes from the ENSO in the previous winter to late spring and early summer with seasonal changes (Liang et al., 2018). During the positive phase of the IOP, the strong warming of the Indian Ocean triggers a strong Indian monsoon. This leads to a strengthening of the WPSH and an increase in precipitation in southern China. The southwestern rapids, which are enhanced by the positive IOP, also provide sufficient water vapor and warm advection to generate favorable conditions for the development of the Jianghuai cyclone.

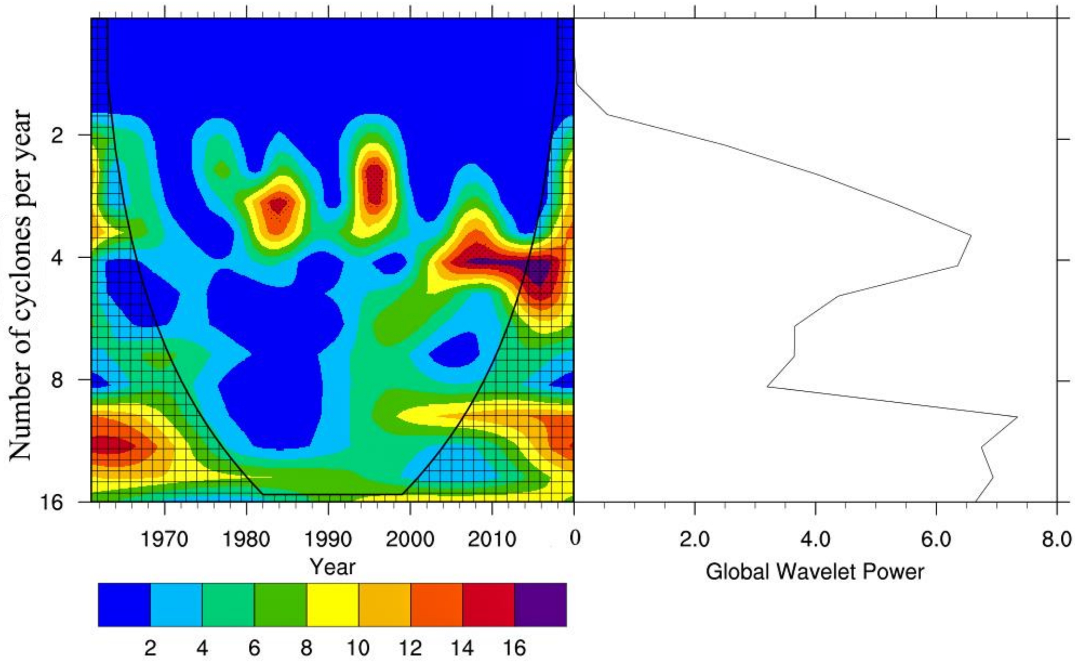

Fig 5. Periodic wavelet analysis diagram of Jianghuai cyclones during the Meiyu period from 1961 to 2020 (units: year) (shadow indicates passing the 95% confidence interval according to the T test).

Jianghuai cyclones are not only characterized by multiperiod variability but also have significant interdecadal variability. Figure 5 shows the activity frequency anomaly and 5-year sliding average of cyclones during the Meiyu period from 1961 to 2020. The frequency of cyclone activity was the highest in 1996 and the lowest in 1961 and 2009. In the long term, the frequency of cyclone activity in the middle and lower reaches of the Yangtze River increased in 1965-1970, in 1990-2000 and after 2010. It decreased in 1970-1990 and 2000-2010. The interdecadal variability trend of Jianghuai cyclones is similar to the interdecadal variability trend of precipitation during the Meiyu period (Chen et al., 2019).

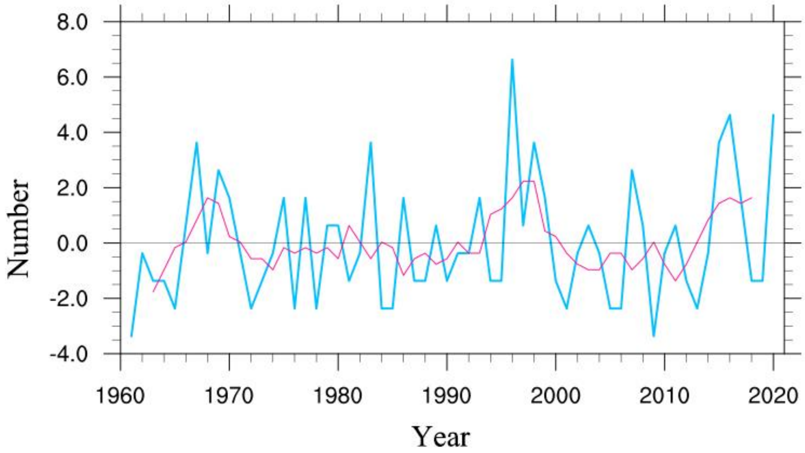

Fig 6. Frequency anomaly and 5-year sliding average of cyclones. The blue line shows the anomalies in the number of cyclones, and the pink line shows the 5-year sliding average of the anomalies.

3.2 Linkage between cyclone activity and concurrent rainfall in the middle and lower reaches of the Yangtze River.

The Jianghuai cyclones are mainly active in the middle and lower reaches of the Yangtze River (Huang et al., 2019; Li et al., 2002). Under the influence of the strengthening westward extension of the WPSH during the Meiyu period, the Jianghuai cyclones are restricted from entering the sea to some extent (Qin et al., 2015; Wu et al., 2020). They form rainstorms and gales in the middle and lower reaches of the Yangtze River and the coastal areas. A large part of the precipitation in the Meiyu period comes from cyclone precipitation (Zhang et al., 2018). The intensity of Meiyu is usually expressed by the Meiyu intensity index. The intensity of precipitation is affected not only by precipitation but also by the number of precipitation days in the Meiyu period. Both jointly determine the intensity of Meiyu in that year.

The time-series plots of the number of cyclones related to precipitation and the intensity index during the Meiyu period from 1961 to 2020 are given in Figure 6a and 6b. We found that the number of cyclones has a positive correlation coefficient of 0.769 with precipitation in the Meiyu period passing the 99% confidence interval according to the T test. The number of cyclones was also positively correlated with the Meiyu intensity index, with a correlation index of 0.760 passing the 99% confidence interval according to the T test. The frequency of Jianghuai cyclone activity in years with a strong Meiyu index is high; the frequency of Jianghuai cyclone activity in years with a weak Meiyu index is low.

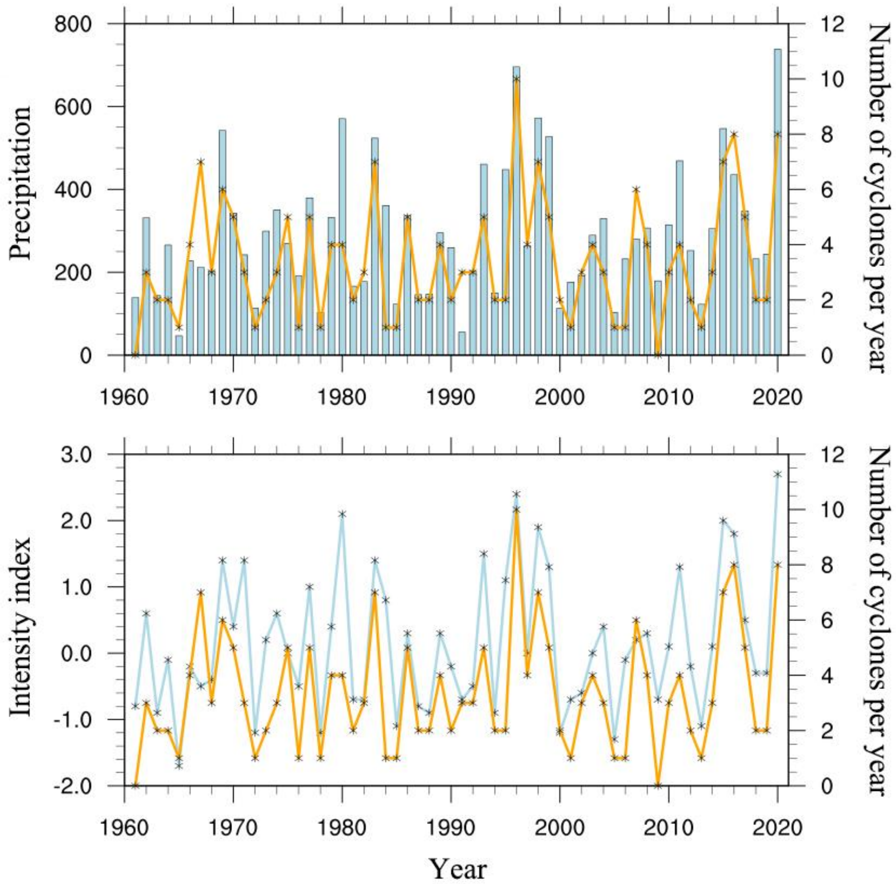

Fig 7. (a) Changes in precipitation (blue bar chart) (unit: mm/day) and the number of cyclones (orange line); (b) intensity index (blue line) and the number of cyclones (orange line) in the Meiyu period from 1961 to 2020.

Figure 8a shows the spatial distribution of annual average precipitation during the Meiyu period from 1961 to 2020. The areas with large precipitation values in the middle and lower reaches of the Yangtze River are mainly located in the Dabie Mountains of Anhui Province, the northern part of Jiangxi Province, the eastern part of Hubei Province and the western part of Hubei Province. The maximum annual average precipitation during the Meiyu period in southern Anhui can even exceed 480 mm. The occurrence of large precipitation areas during the Meiyu period is closely related to the topography of the region (Wu et al., 2023).

If precipitation and Jianghuai cyclone activity existed on the same day during the Meiyu period, we defined that day as a Jianghuai cyclone precipitation day. The remaining days in the Meiyu period were treated as non-Jianghuai cyclone precipitation days. Figure 8b shows the spatial distribution of the proportion of cyclone precipitation relative to total precipitation during the Meiyu period. As shown in the figure, the main areas affected by cyclone precipitation are the middle and lower reaches of the Yangtze River. The Huaihe River basin in northern Anhui Province is the most affected area. The cyclone precipitation in the Huaihe River basin accounts for more than 47% of the total precipitation during the Meiyu period, while the cyclone-influenced precipitation in other areas accounts for more than 35% of the total precipitation. In general, the degree of cyclone-influenced precipitation in the middle and lower reaches of the Yangtze River shows an east–west band distribution and a gradual decrease from coastal to inland areas. This indicates that the distribution of the large-value area and the characteristics of the band distribution are related to the northeast and eastward tracks of the Jianghuai cyclone. Its precipitation capacity gradually increases with the development of cyclone movement.

Figure 8c shows the spatial distribution of the daily mean precipitation anomaly of the Jianghuai cyclone. The shaded part indicates that the 95% confidence interval is passed according to the T test. The anomaly is based on the whole Meiyu period from 1961 to 2020 (The exceptions mentioned below are also based on the whole Meiyu period from 1961 to 2020). When the Jianghuai cyclone is active, the middle and lower reaches of the Yangtze River to the east of 108°E show an abnormal increase in precipitation. However, Fujian, Guangdong and other places show an abnormal decrease. Among them, the maximum value of abnormally increased precipitation can exceed 7 mm/day in areas such as southern Anhui, eastern Hubei and northern Jiangxi. The large-value areas of precipitation anomalies are consistent with the large-value areas of cyclone occurrence frequency sources. It is inferred that the spatial distribution of precipitation anomalies has a connection with the distribution of cyclone genesis locations. This phenomenon of increasing and decreasing precipitation anomalies is bounded by approximately 27°N and distributed north–south in the form of dipoles.

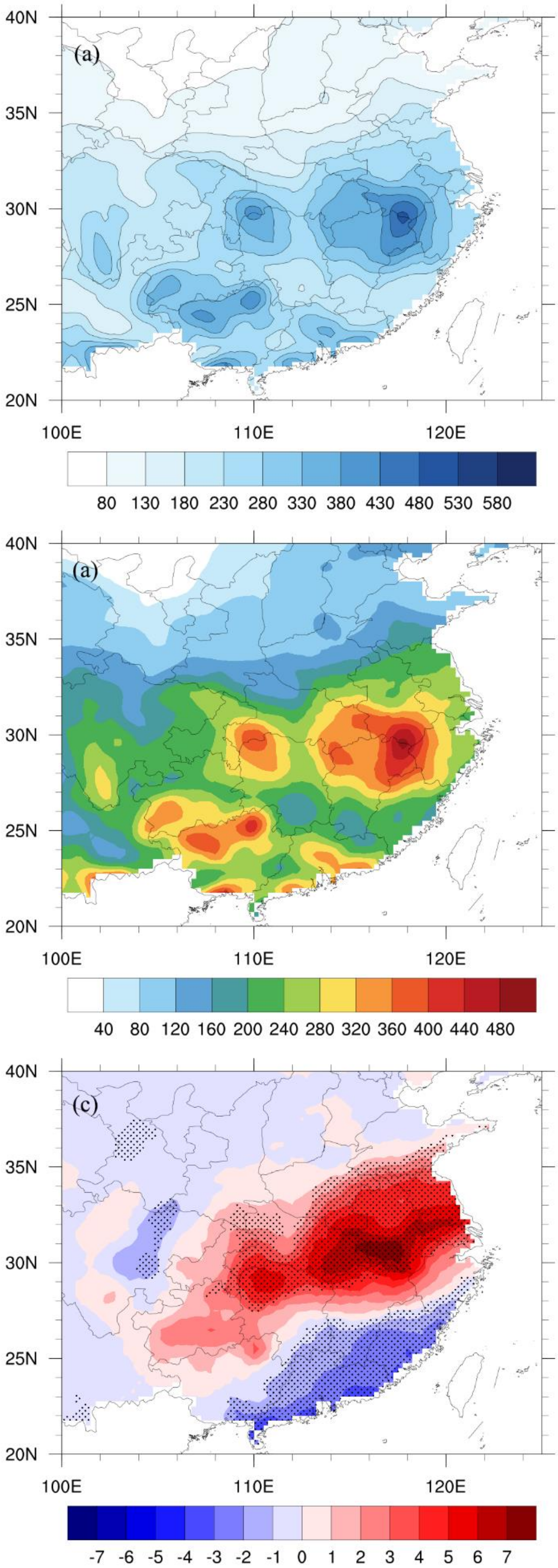

Fig 8. (a) Annual mean precipitation during the Meiyu period from 1961 to 2020 (units:

mm/year); (b) proportion of Jianghuai cyclone precipitation relative to total precipitation during the Meiyu period (units: %); (c) daily mean precipitation anomaly of the Jianghuai cyclone during the Meiyu period (units: mm/day) (shadow indicates passing the 95% confidence interval according to the T test).

Figure 9 shows the evolution of composite geopotential height and horizontal wind anomalies for three different levels of Jianghuai cyclones from day -4 to +2 during the Meiyu period. Composite geopotential height anomalies are significant at the 95% confidence level based on a T test. Vectors are plotted if wind anomalies are significant at the 95% confidence level based on a T test in at least one direction.

Day 0 is the day on which the cyclone first appears in the specified area. Most areas of the lower and middle troposphere (700 hPa, 850 hPa) in the middle and lower Yangtze River on day 0 are covered by significant negative geopotential height anomalies with peak magnitudes greater than -11 gpm. There is a significant positive geopotential height anomaly with a peak magnitude of over 13 gpm on the southeast side of the negative geopotential height anomaly. These anomalies form meridional dipole structures in the middle and lower troposphere geopotential height field. The southwest wind anomaly is significant in the middle and lower reaches of the Yangtze River. The south of Anhui Province and the north of Jiangxi Province are between the positive geopotential height anomaly and negative geopotential height anomaly. The existence of these anomalies indicates the enhancement of southwest rapids and the strengthening of the WPSH. The negative geopotential height anomalies at 500 hPa height on day 0 are mainly in Mongolia, Shanxi and other places. Strong southwest wind anomalies exist between the positive and negative geopotential height anomalies. The negative geopotential height anomalies in the Mongolian region exceed -7 gpm.

The negative geopotential height anomalies on all three isobaric surfaces can be traced back to Mongolia, Inner Mongolia and part of Northeast China on day -2. Negative geopotential height anomalies at 500 hPa can be traced to day -4. On day -4, significant southwestern wind anomalies exist in southwestern Hunan at 700 hPa and

850 hPa. Significant northwest wind anomalies exist in the Yellow River basin of China at 500 hPa. By day -2, the negative geopotential height anomalies in Mongolia, Inner Mongolia and some northeastern areas are enhanced for all three isobars. The positive geopotential height anomalies of the WPSH are enhanced and extend northward to the southern part of the middle and lower reaches of the Yangtze River. There are significant southwest wind anomalies at the three isobaric surfaces in the south of the middle and lower reaches of the Yangtze River, while there are significant northwest wind anomalies at 500 hPa in the north of Anhui Province and Jiangsu Province. The negative geopotential height anomalies on the three isobaric surfaces move eastward with the formation and development of Jianghuai cyclones. On day +2, the lower reaches of the Yangtze River are mainly affected by the combined action of anomalous southwest winds and northwest winds. The positive geopotential height anomaly of the WPSH is weakened.

Therefore, the abnormal precipitation caused by the Jianghuai cyclone mainly comes from the abnormal southwest winds and the strengthening of the WPSH. The enhanced southwest jet provides sufficient warm and moist air for the formation of cyclones and promotes the eastward migration of cyclones after formation. Liu et al. (2020) and Zhao et al. (2021) studied the causes of the super strong Meiyu year in 2020, mentioned that the WPSH is unusually strong and westward accompanied by an abnormal increase in precipitation. Liu et al. (2020) found that the enhanced southwest jet stream is conducive to the development of vertical movement in the middle and low levels, which provides the necessary dynamic conditions for the formation of sustained precipitation during the Meiyu in 2020.

Cold air activity is one of the important factors for the formation of heavy precipitation, which can promote the convergence and uplift of low level necessary for heavy precipitation (Liu et al., 2020). The enhanced negative geopotential anomaly over Mongolia provides cold and dry air brought by the westerly jet for cyclone development. The increasing frequency of cyclones over the Yangtze River and Huaihe River leads to the abnormal increase in precipitation in the middle and lower reaches of the Yangtze River during the Meiyu period. However, due to the strengthening of the WPSH, the southern part of China is controlled by the abnormal positive geopotential height, and the precipitation decreases. Zhao et al. (2021) also found that when the WPSH enhanced, there was a decrease in precipitation in South China.

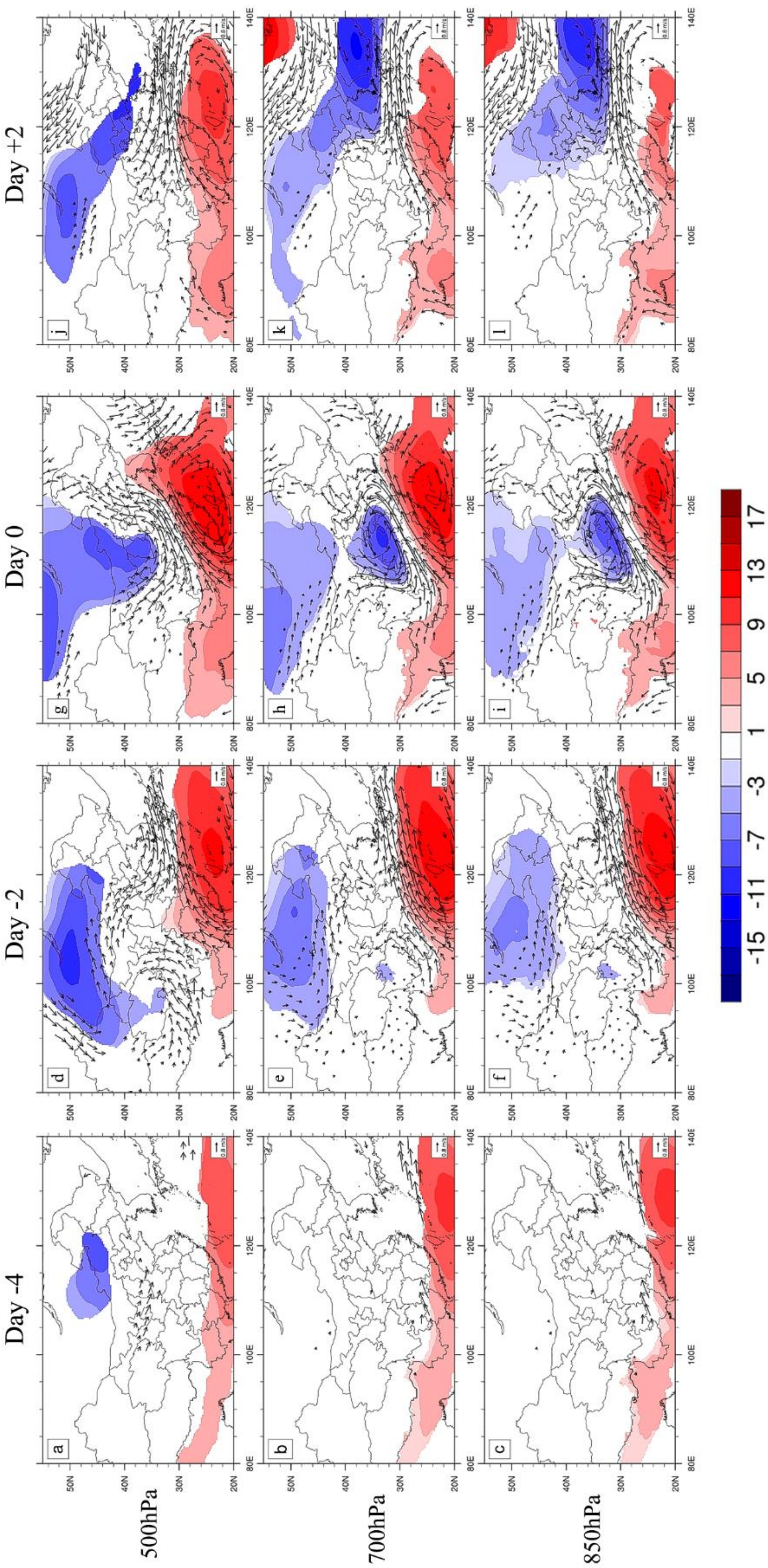

Fig 9. Evolution of composite geopotential height anomalies (shading; units: gpm) and horizontal wind anomalies (units: m/s) on the 850 hPa, 700 hPa, and 500 hPa isobaric surfaces for day −4 (a–c), day −2 (d–f), day 0 (g–i) and day +2 (j–l) for the 202 selected Jianghuai cyclones. Shading indicates that composite geopotential height anomalies are significant at the 95% confidence level based on a T test. Vectors are plotted if wind anomalies are significant at the 95% confidence level based on a T test in at least one direction.

Figure 10 shows the climatic distribution of water vapor flux and water vapor flux divergence at a pressure level of 850 hPa during the Meiyu period. The water vapor involved in the precipitation process of the Jianghuai cyclone during the Meiyu period mainly comes from the water vapor brought by the southwest jet of the summer monsoon in the low-latitude area. During Jianghuai cyclone development, the middle and lower reaches of the Yangtze River are mostly in the water vapor convergence area, which is conducive to the generation of precipitation (Chen et al., 2020).

Figure 11 shows the distribution of water vapor flux anomalies and water vapor flux divergence anomalies at the pressure level of 850 hPa during the Jianghuai cyclone from day -2 to day +2. The color field and wind vector arrows in the figure both passed the 95% significance according to the T test. On day -2, a significant water vapor convergence anomaly and water vapor transport in the southwest direction appear in southern Anhui Province. The anomalies of water vapor flux and water vapor flux dispersion are mainly concentrated on day 0. There is significant anomalous water vapor convergence up to -1 $g \cdot cm^{-2} \cdot hPa^{-1}$ in eastern Hubei Province, Anhui Province and Jiangsu Province on day 0. Anomalous water vapor dispersion exists in the southern part of the middle and lower reaches of the Yangtze River and some areas in southern China. On day +2, with the development of the cyclone's eastward movement, only the southern part of Jiangsu Province and the northern part of Zhejiang Province have abnormal water vapor flux in the eastward direction. The precipitation in the area begins to gradually weaken at this time.

From day -2 to day 0, the abnormal water vapor flux and water vapor flux divergence configuration make the warm and wet air in the low-latitude area transport to the middle and lower reaches of the Yangtze River. The abnormal water vapor flux has a negative value, water vapor convergence occurs, local water vapor volume increases, and finally, the precipitation in the region increases. Liu et al. (2020) studied the strong rainfall in 2020, they found that there was an enhanced water vapor transport, and the repeated occurrence of convergence movement. Both of them caused the precipitation time to increase in the Jianghuai River basin.

In contrast, the anomaly of water vapor flux in southern Guangdong and other regions is divergent. This leads to a decrease in local water vapor volume and precipitation in this region. These results indicate that the variations in water vapor flux and divergence related to cyclones are mainly from warm and wet air transported from low latitudes to the middle and lower reaches of the Yangtze River. Therefore, there is a positive correlation between cyclone activity and precipitation in the middle and lower reaches of the Yangtze River.

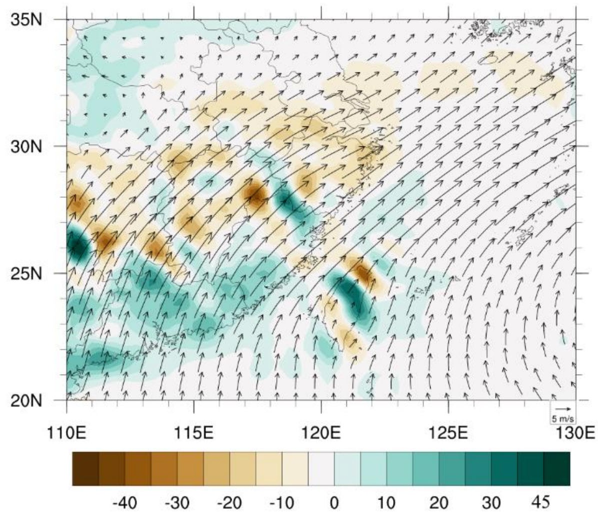

Fig 10. Distribution of 850 hPa daily mean water vapor flux (unit: $g \cdot cm^{-2} \cdot hPa^{-1}$) and water vapor flux divergence (unit: 10^{-8} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$) of cyclones over the Yangtze and Huaihe rivers during 1961-2020 (color diagram shows water vapor flux divergence, and vector diagram shows water vapor flux).

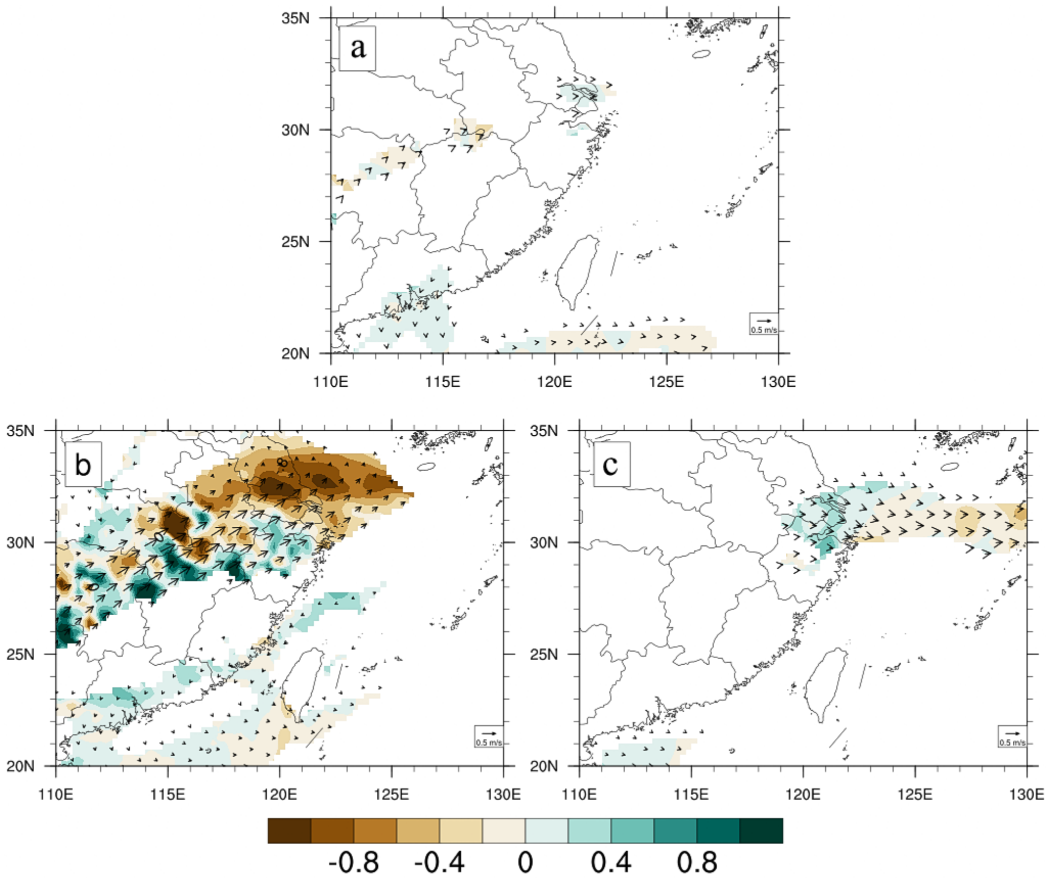

Fig 11. Distribution of the 850 hPa daily mean water vapor flux anomaly (unit: $g \cdot cm^{-2} \cdot hPa^{-1}$) and water vapor flux divergence anomaly (unit: 10^{-8} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$) of cyclones over the Yangtze and Huaihe rivers during 1961-2020 (color diagram shows water vapor flux divergence, and vector diagram shows water vapor flux). The colored region passed the 95% confidence interval according to a T test. If the vapor flux anomaly is significant at the 95% confidence level for the T test in at least one direction (zonal or meridian), the vector is plotted.

4. Summary and discussion

Based on ERA5 reanalysis of sea level pressure data and using the relative vorticity method to identify and track cyclones, we have examined the impacts of the climatological characteristics of Jianghuai cyclones. The linkages between cyclone activity and precipitation in the middle and lower reaches of the Yangtze River during the Meiyu period are also analyzed.

During the Meiyu period, Jianghuai cyclones are mainly generated at the junction of western Hubei and Chongqing Municipality, eastern Hubei Province, northern Jiangxi Province, central and southern Anhui Province, and Jiangsu and Zhejiang provinces. These cyclones develop and move to the sea in the east or northeast direction. There is a positive correlation between the maximum intensity and maximum radius of Jianghuai cyclones. The higher the cyclone intensity is, the larger the radius will be. Its occurrence frequency not only has the characteristics of multicycle variation but also has obvious interdecadal variation, which has a good correspondence with the periodic and interdecadal variation in precipitation in the Meiyu period.

There is a positive correlation between the frequency of cyclone activity and precipitation in the Meiyu period. The frequency of Jianghuai cyclone activity is high in the years with strong Meiyu rainfall and low in the years with weak Meiyu rainfall. The percentage of precipitation affected by Jianghuai cyclone activity in the middle and lower reaches of the Yangtze River can reach up to 47%. The spatial distribution is in the shape of an east–west belt, and the degree of influence gradually decreases from the coast to the interior. When the Jianghuai cyclone is active, the precipitation increases abnormally in the middle and lower reaches of the Yangtze River east of 108°E. Precipitation decreases abnormally in Fujian Province and Guangdong Province. The spatial distribution of precipitation anomalies is related to the genesis locations of cyclone frequency, and the positive and negative anomalies are distributed north–south in the form of dipoles based on the latitude line at approximately 27°N as the boundary.

The geopotential height anomaly field and the horizontal wind vector anomaly field of the Jianghuai cyclones during the Meiyu period are synthesized and analyzed. There is an enhanced positive geopotential height anomaly of the WPSH during cyclone activity. The negative geopotential altitude anomaly of Mongolia and the abnormal southwest jet are enhanced. All of these factors lead to an increase in precipitation in the middle and lower reaches of the Yangtze River. The abnormal leading signal of the negative geopotential height in Mongolia can be traced to day -2 of the cyclone activity, and the signal can be traced to day -4 at 500 hPa. From day -2 to day 0 of cyclone activity, the abnormal distribution of water vapor flux and water vapor flux divergence cause the warm and wet air at the low latitudes to be transported to the middle and lower reaches of the Yangtze River. They promote the generation and development of cyclones and increase precipitation in the middle and lower reaches of the Yangtze River.

We explored the cyclone characteristics and study emphasizes the link between cyclone activity and Yangtze River precipitation. Spatially, abnormal precipitation patterns are identified, tracing the evolution of geopotential height anomalies and water vapor flux. But the specific mechanism by which the southwest jet affects cyclones during the Meiyu period is not clear enough. Zhang et al. (2018) suggest that the strengthening of the Southwest jet will lead to the development of α mesoscale low-pressure disturbance near the Meiyu Front and the occurrence of extreme precipitation. Liu et al. (2020) found that the strengthening of the southwest jet made the southerly meridional strong gradient zone on the north side of the meridional wind maximum center move northward in the low-level dynamic conditions of the rainstorm process during Meiyu. How the Southwest jet stream influences the development of physical factors to promote the formation of Jianghuai cyclones remains to be considered and analyzed. Zhao et al. (2010) found that the causes of Jianghuai cyclones with different intensities were different through a case study. Therefore, we think it is also necessary to consider the difference in the influence of different intensities of Jianghuai cyclones on precipitation. These problems need further analysis and research.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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