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An unusual Northwest–Southeast oriented Meiyu rain belt in 2021

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Affected by the East Asian summer monsoon, summer floods occur frequently in eastern China, causing huge economic losses and social impacts. In 2021, the precipitation anomaly during the Meiyu period in Yangtze-Huaihe River Valley (YHRV) was abnormally high, with a value of 188.0 mm, about 1.7 standard deviations above normal. However, it did not cause serious flood disasters. This was mainly due to the existence of two precipitation anomaly centers in YHRV, which shared the impact of the excessive precipitation. These two centers were located at the junction of Anhui Province and Henan Province and the junction of Jiangsu Province, Anhui Province and Jiangxi Province, respectively. And more notably, the 2021 Meiyu precipitation anomalies were distributed in a Northwest-Southeast oriented band that is very rare. During the 2021 Meiyu period, the western Pacific subtropical high (WPSH) weakened and extended westward. An anticyclonic circulation anomaly in the lower troposphere was observed over eastern China, which was found to be related to the quasi-stationary wave trains propagating eastward from Hainan Island to the northwestern Pacific by vorticity budget analysis. And the Rossby wave source term played a critical role. In addition, the tropical Atlantic anomalous warming produced convergence anomaly over the eastern Mediterranean and excited quasi-stationary wave trains propagating downstream at the mid-latitudes in upper layers through a monsoon-desert-like teleconnection. It raised the geopotential height over eastern China and thus favored the westward extension of WPSH. These large-scale circulation anomalies generated the anomalous easterly winds along the eastern coast of China and the anomalous southwesterly winds from Guangxi Province to the middle and lower reaches of the Yangtze River. Similar features can be found in the anomalous water vapor transport and the water vapor converged in the YHRV. The above-mentioned reasons jointly caused the abnormally high precipitation anomaly and its unusual pattern in the 2021 Meiyu season. This study might provide a scientific basis and clues for understanding Meiyu precipitation anomalies and disaster prevention and mitigation.

KEYWORDS

2021 Meiyu season, Northwest-Southeast oriented rain belt, precipitation anomaly, western Pacific subtropical high, tropical Atlantic, atmospheric circulation anomalies

1 Introduction

Eastern China, the densely populated and the most developed region in China, is also one of the major crop production areas. Influenced by the East Asian summer monsoon (EASM), floods occur frequently in eastern China. In the summer of 1998, a devastating flood occurred on the Yangtze River, which caused over 3,000 deaths and disappearances, and resulted in 260 billion RMB in direct economic losses (Huang et al., 1998). During the summer of 2020, the middle and lower reaches of the Yangtze River suffered a persistent extremely heavy precipitation event (Liu et al., 2020; Takaya et al., 2020; Wang et al., 2021; Zhou et al., 2021) that resulted in more than 140 deaths or missing persons, and 76 billion RMB in direct economic losses (Ding et al., 2021). The summer flooding events in the Yangtze River Basin seriously affect the local people's life and socio-economic development.

The precipitation during the flood season of the Yangtze River Basin is closely tied to the Meiyu period from mid-June to mid-July (Ding et al., 2021). During the Meiyu period, the rain belt in eastern China is mainly located in the middle and lower reaches of the Yangtze River. The high values of average precipitation are situated in the southern Anhui Province and the junction of Anhui Province, Fujian Province, and Zhejiang

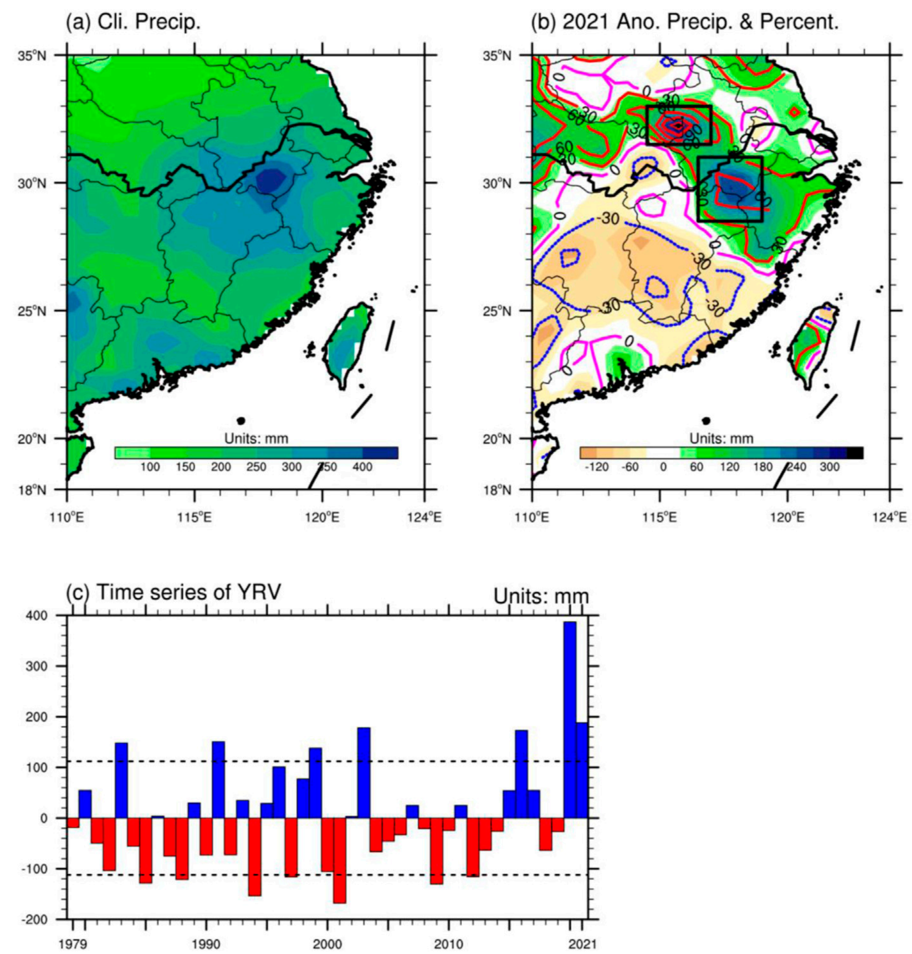

FIGURE 1
(A) 1979–2021 climatological mean precipitation (shading, units: mm) during Meiyu period (from 10 June to 11 July); **(B)** Anomalous precipitation (shading, units: mm) and percentage of precipitation anomaly (contours, units: %). The red solid (blue dotted) line represents a positive (negative) percentage, and the magenta solid line denotes zero values; **(C)** Time series of the regional mean [two rectangular regions showed in **(B)**] precipitation anomaly (units: mm) over Yangtze-Huaihe River Valley (YHRV) during Meiyu period.

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Province, with an extreme value exceeding 400 mm (Figure 1A). The Meiyu precipitation over the Yangtze River Basin is usually distributed in a Southeast-Northwest or East-West oriented narrow belt. For instance, the Yangtze River basin suffered from persistent extreme heavy precipitation events in the 2020 Meiyu season, with an almost West-East oriented rain belt along the Middle and Lower of the Yangtze River (Liu et al., 2020; Takaya et al., 2020; Wang et al., 2021; Zhou et al., 2021). In 2021, the Meiyu season started on 10 June and ended on 11 July, lasting for 31 days. However, the spatial distribution of the precipitation anomaly in the 2021 Meiyu period exhibited an unusual Northwest-Southeast tilted feature, which was different from the typical Meiyu rain belt. There were two dominant precipitation anomaly centers. One was located at the junction of Anhui Province and Henan Province, and the extreme value of precipitation anomaly exceeded 300 mm and the corresponding precipitation anomaly percentage exceeded 150%. The other large value center was situated at the junction of Jiangsu Province, Anhui Province, and Jiangxi Province, with an anomalous precipitation extreme value greater than 240 mm and a precipitation anomaly percentage extreme value exceeding 60%. In the eastern Hubei Province, there were negative precipitation anomalies, with a minimal value of less than -90 mm and a precipitation anomaly percentage of less than −30% (Figure 1B).

The time series of regional-averaged precipitation (two rectangular areas shown in Figure 1B) during the Meiyu period in Yangtze-Huaihe River Valley (YHRV) for 1979–2021 show that there are not only significant interannual and interdecadal variations but also obvious long-term trends in Meiyu precipitation of YHRV (Figure 1C). The mean Meiyu precipitation in the YHRV is 289.3 mm for 1979–2021, with a standard deviation of 112.1 mm. The highest Meiyu total precipitation occurred in 2020 (Ding et al., 2021), with a precipitation anomaly of 386.9 mm. During the 2021 Meiyu period, the total precipitation in the YHRV is the second most in the past four decades. And the precipitation anomaly was 188.0 mm, about 1.7 standard deviations. It can be seen that during the 2021 Meiyu season, the precipitation anomaly in YHRV was positive. In addition, different from the zonal distribution of precipitation in typical Meiyu years, the precipitation anomaly was distributed in a southeast-northwest trending narrow area.

There are numerous factors influencing the Meiyu precipitation in YHRV. The EASM system and the Meiyu precipitation anomaly are closely linked (Ding, 2004; Zhang, 2015). El Niño-Southern Oscillation (ENSO) is an important air-sea coupling phenomenon in the tropics. It is found that ESNO can regulate the anomalies of the EASM system (Wang et al., 2000; Xie et al., 2009), and thus exerts important effects on Meiyu precipitation anomalies (Zhang et al., 1996; Xie et al., 2010; Jin et al., 2016). Northern Atlantic Oscillation (NAO; Walker and Bliss, 1932; Hurrell, 1995) can modulate the summer precipitation anomaly in East Asia by affecting the atmospheric teleconnection in the upper troposphere at mid-high latitudes (Wu et al., 2009; Jin and Guan, 2017; Liu et al., 2020). The tropical Atlantic sea surface temperature (SST) anomaly regulates the western Pacific subtropical high (WPSH) and then influences the Meiyu precipitation anomaly in YHRV (Jin and Huo, 2018). Furthermore, the soil moisture of the Indo-China Peninsula in early spring (Gao et al., 2020), the Arctic Oscillation (Gong et al., 2002), and the Antarctic Oscillation (Nan and Li, 2003) can also affect the precipitation during the flood season of YHRV.

To investigate the causes of the abnormal precipitation and its atypical pattern in 2021 Meiyu season, this study focuses on the atmospheric circulation anomalies associated with the WPSH and the tropical Atlantic SST. The remainder of this paper is organized as follows: Section 2 describes the data and methods used in this paper. The causes of precipitation anomaly and its spatial distribution in the 2021 Meiyu season are presented in Section 3. The conclusion and discussion are provided in Section 4.

2 Data and methods

The NCEP/NCAR daily reanalysis data with a horizontal resolution of 2.5°×2.5° (Kalnay et al., 1996) and daily precipitation data of Climate Prediction Center (CPC) with a horizontal resolution of 0.5°×0.5° for 1979–2021 are utilized (Chen et al., 2008). The Meiyu season in 2021 started on 10 June and ended on 11 July. Therefore, this period is taken as the Meiyu period to obtain the average value of each variable in this study. The COBE monthly SST data with a horizontal resolution of 1° × 1° are also obtained (Ishii et al., 2005). The long-term trends are deducted from all data except that the raw data are used in Figure 2B to show the contour line of 588 dagpm. The anomaly in this paper is defined as the deviation of the Meiyu period from the climatological mean for 1979–2021.

Linear vorticity equation (Kosaka and Nakamura, 2006) is utilized in Section 3.2 to analyze the vorticity budget:

$$S \underbrace{-\bar{u}_\psi \frac{\partial \zeta'}{\partial x}}_{ZA} \underbrace{-\bar{v}_\psi \frac{\partial \zeta'}{\partial y}}_{MA} \underbrace{-u'_\psi \frac{\partial \bar{\zeta}}{\partial x} - v'_\psi \frac{\partial (f+\bar{\zeta})}{\partial y}}_{\beta} - R_{res} = 0$$

where S denotes the linearized Rossby wave source (RWS) (Sardeshmukh and Hoskins, 1988):

$$S = -\nabla_H \cdot \left\{ \mathbf{u}'_\chi (f+\bar{\zeta}) \right\} - \nabla_H \cdot \left(\bar{\mathbf{u}}_\chi \zeta' \right)$$

ZA and *MA* are mean zonal and meridional advection of anomalous vorticity, respectively. β term represents the horizontal advection of the mean absolute vorticity by anomalous winds. R_{res} denotes the residual term.

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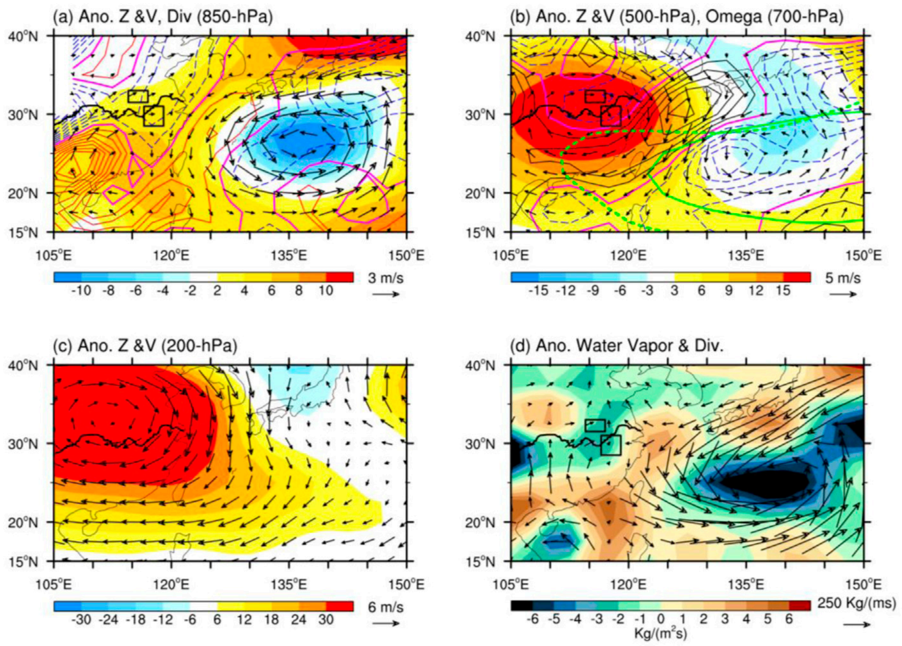

FIGURE 2
(A) Anomalous geopotential height (shading, units: gpm), divergence (contours, units: 10^{-6} s^{-1}) and winds (vectors, units: m/s) at 850-hPa during 2021 Meiyu period; **(B)** Anomalous geopotential height (shading) and winds (vectors) at 500-hPa, and anomalous vertical velocity (units: Pascal/s) at 700-hPa during 2021 Meiyu period; **(C)** Anomalous geopotential height (shading) and winds (vectors) at 200-hPa during 2021 Meiyu period; **(D)** Anomalous water vapor flux (vectors, units: kg/ms) integrated from surface to 300-hPa and its divergence (shading, units: kg/m^2s) during 2021 Meiyu period. The red solid/blue dashed line represents divergence/convergence anomaly, and the magenta solid line denotes zero values in **(A)**. The black solid line, magenta solid line, and blue dashed line in **(B)** represent positive, zero, and negative values, respectively. The green solid and dashed lines in **(B)** are the 588-dagpm contours for climate mean and for the 2021 Meiyu period, respectively.

3 Results

The precipitation anomaly during the Meiyu season in East Asia is closely related to the WPSH (e.g., Wang et al., 2000; Jin and Huo, 2018; Qian and Guan, 2020; Zhou et al., 2021). Therefore, from the perspective of local atmospheric circulation anomaly and SST anomaly, the following paper aims to explore the causes of the abnormal total precipitation over YHRV in 2021 Meiyu and the atypical pattern of precipitation anomaly.

3.1 Local atmospheric circulation anomaly

During the 2021 Meiyu season, a cyclonic anomaly and a negative geopotential height anomaly center appeared in the lower troposphere over the northwestern Pacific. And an anticyclonic anomaly and a positive geopotential height anomaly center can be seen from the South China Sea to the middle and lower reaches of the Yangtze River. Abnormal easterly winds prevailed from the Kuroshio extension area to the coastal region of eastern China. And the region from Guangxi Province to the middle and lower reaches of the Yangtze River was controlled by the anomalous southwesterly winds. These two branches of anomalous airflows converged in YHRV (Figure 2A). The convergence anomaly was observed in the middle and lower troposphere over YHRV (Figures 2A,B). Above circulation anomalies were conducive to the anomalous upward motion in the middle and lower troposphere (Figure 2B), and thus increased precipitation over YHRV.

Note that the negative geopotential height anomaly and cyclonic anomaly in the middle and lower troposphere were maintained over the northwestern Pacific (Figures 2A,B) during the 2021 Meiyu period. The regional average geopotential height anomaly within [20–30°N, 130–150°E] at 850-hPa was calculated as the WPSH index according to the scope of the area with the large absolute value of the negative geopotential height anomaly in the lower troposphere (Figure 2A). It is found that the WPSH index during the 2021 Meiyu period was −0.35 standard deviation, indicating that the intensity of WPSH during the 2021 Meiyu period was weaker than the climate mean. However, the location of WPSH showed by 588 dagpm isoline was approximately 10 longitudes west compared with its climate mean position. And it approximately extended to 112°E (Figure 2B) in the 2021 Meiyu period, which signs that the WPSH during this period was characterized by a relatively large range and a westward extension.

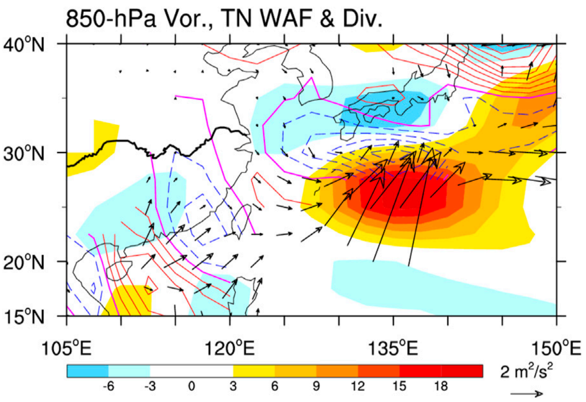

FIGURE 3
Anomalous vorticity (shading, units: 10^{-6}/s), wave activity flux (vectors, units: m^2/s^2) and its divergence (contours, units: 10^{-5} m/s^2) at 850-hPa during the 2021 Meiyu period. The red solid (blue dashed) line represents divergence (convergence), and the magenta solid line denotes zero values.

As shown in Figure 2C, a positive anomaly center of geopotential height anomaly and an anticyclonic anomaly appeared over eastern China and the adjacent ocean. Meanwhile, a positive geopotential height anomaly and an anticyclonic anomaly in the middle (500-hPa) and lower (850-hPa) troposphere were located over eastern China (Figures 2A,B), denoting that the anticyclonic circulation anomaly in eastern China showed an equivalent barotropic structure. However, in the middle and upper troposphere, the area to the north of YHRV was controlled by anomalous westerly winds (Figures 2B,C), suggesting that the positive precipitation anomaly and its unusual pattern over YHRV in the 2021 Meiyu season may also be related to the circulation anomaly in the upper troposphere at mid-latitudes. This will be further analyzed in the following.

The integrated water vapor flux anomaly and its divergence during the 2021 Meiyu period in Figure 2D show that there was anomalous anticyclonic (cyclonic) transport of water vapor over the south of the Yangtze River (northwestern Pacific). Due to the weakened WPSH, the abnormal water vapor was transported from the Kuroshio extension area to the middle and lower reaches of the Yangtze River along the northern side of WPSH (Figures 2A,B). The other branch of abnormal water vapor was transported from the South China Sea to the JHRV along the western side of WPSH, which was due to the expanded range of WPSH and the westward extension of the ridge point (Figure 2B). These two branches of anomalous water vapor converged in JHRV, and the convergence center was located over JHRV (the two rectangular boxes as shown in Figure 2D), which was primarily responsible for the excessive precipitation and the atypical spatial distribution of precipitation anomaly in JHRV.

3.2 Influence of quasi-stationary wave trains

To explore the mechanism of WPSH affecting the atypical precipitation anomaly pattern during the 2021 Meiyu period, we analyzed the Rossby wave energy dispersion in the lower troposphere over the western Pacific, followed by Takaya and Nakamura (2001).

The wave activity fluxes dispersed northeastward from the east of Hainan Island to the Kuroshio extension area (Figure 3), showing a typical great circle path (Hoskins and Karoly, 1981). The Rossby wave energy diverged over the east of Hainan Island, while converged over the south of the Yangtze River and the northwestern Pacific. The disturbances of Rossby wave energy in the above two regions enhanced the anticyclonic anomaly over eastern China and the cyclonic anomaly over the northwestern Pacific, respectively (Figure 2A). The anomalous positive vorticity (Figure 3) and convergence (Figure 2A) were observed over the east of Hainan Island, which manifests the airflow converged here and the quasi-stationary wave trains were excited and propagated northeastward.

To further study the structure of wave trains propagating from the east of Hainan Island to the northwestern Pacific, we diagnosed the vorticity budget using the linear vorticity equation according to Kosaka and Nakamura (2006).

Figure 4 shows the contributions of 850-hPa RWS, ZA, MA, and β terms to the East Asian circulation anomalies during the 2021 Meiyu period. It can be seen that the RWS term played a critical role in maintaining the low-level anticyclonic anomaly in the south of the Yangtze River (Figure 4A), and the MA term had a positive/negative contribution to the North/South of anticyclonic circulation anomaly (Figure 4C). The β term negatively contributed to the southeast of the anomalous anticyclone circulation (Figure 4D), while the ZA term slightly promoted to the anticyclonic anomaly (Figure 4B).

For the cyclonic anomaly in the northwestern Pacific, the RWS and ZA terms were positive anomalies (Figures 4A,B), facilitating the generation of low-level cyclonic vorticity anomaly in the northwestern Pacific. However, the MA and β terms showed negative anomalies in most of the northwestern Pacific (Figures 4C,D), which thus partially offset the contributions of RWS and ZA terms to the cyclonic vorticity anomaly in the lower troposphere of this region.

3.3 Influence of tropical Atlantic SST anomaly

Although the above analysis denotes that precipitation anomaly during the 2021 Meiyu period was closely related to the anomalous WPSH. However, previous studies indicated that the tropical Atlantic SST anomaly also exerts a dominant influence on East Asian climate anomalies (e.g., Rong et al.,

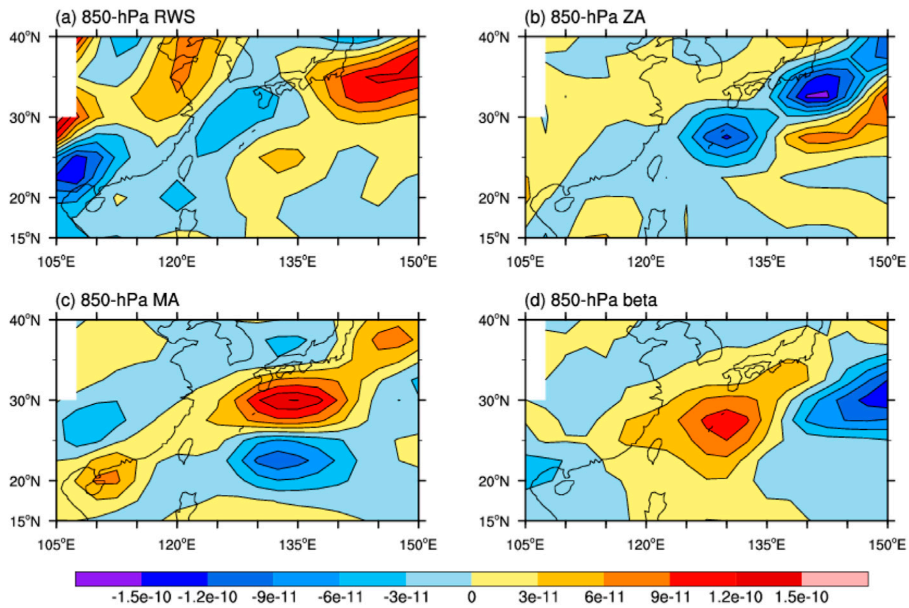

FIGURE 4
Anomalous **(A)** Rossby wave source (RWS), **(B)** mean zonal advection of anomalous vorticity (ZA), **(C)** mean meridional advection of anomalous vorticity (MA), and **(D)** β terms at 850-hPa during the 2021 Meiyu period (units: $10^{-12}/s^2$).

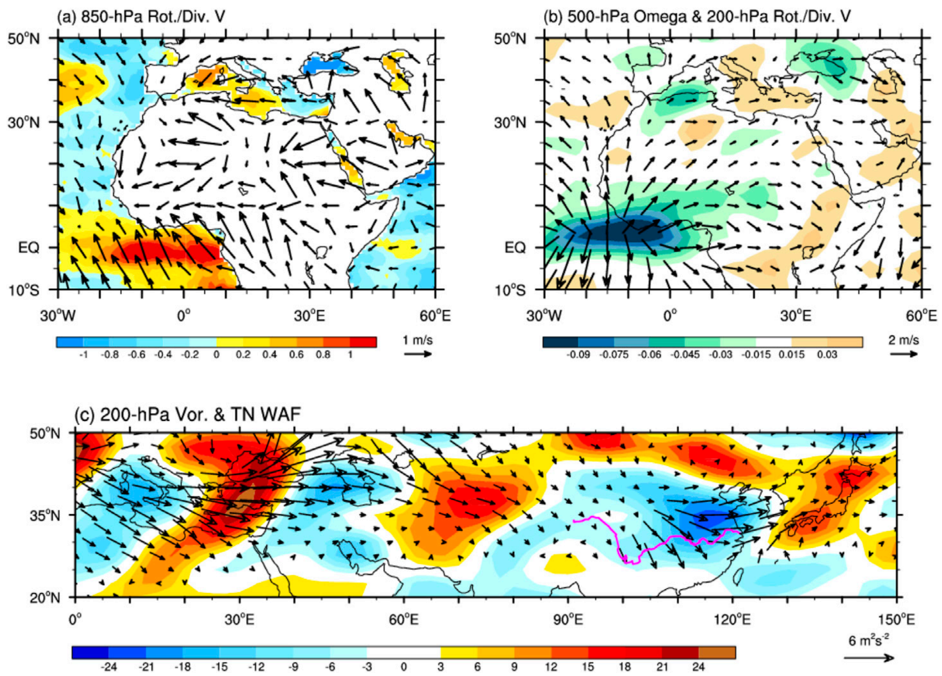

FIGURE 5
(A) Anomalous SST (shading, units: ˚C) and divergent wind (vectors, units: m/s) at 850-hPa; **(B)** Anomalous vertical velocity at 500-hPa (shading, units: Pascal/s) and divergent wind at 200-hPa (vectors, units: m/s); **(C)** Anomalous vorticity (shading, units: $10^{-6}/s$) and wave activity flux at 200-hPa (vectors, units: m^2/s^2) during the 2021 Meiyu period.

2010; Huo et al., 2015; Jin and Huo, 2018; Li et al., 2022). To elucidate whether the precipitation anomaly and atypical pattern of Meiyu rain in 2021 are associated with the tropical Atlantic SST anomaly, we also analyzed the tropical Atlantic SST anomaly and the related circulation anomaly in the 2021 Meiyu season (Figure 5).

During the 2021 Meiyu period, the SST anomaly in the tropical Atlantic [5°S–5°N, 20°W–10°E] was positive with the amplitude exceeding 1°C in most areas (Figure 5A). Such warm SST in the tropical Atlantic led to anomalous convergence in the lower troposphere (Figure 5A), and resulted in upward movement through Ekman pumping and anomalous divergence in the upper troposphere over this region (Figure 5B). The above circulation anomaly caused the anomalous convergence in the upper troposphere and anomalous downdraft over the eastern Mediterranean (Figure 5B), accompanied by the anomalous divergence at low levels (Figure 5A), which is similar to the monsoon-desert-like teleconnection (Rodwell and Hoskins, 1996). The quasi-stationary wave trains propagating downstream along the mid-latitudes were stimulated by the positive vorticity anomaly (Figure 5C) and the RWS term (Figure is not shown) in the upper troposphere over the eastern Mediterranean, which may be correlated to the “Silk Road pattern” (Lu et al., 2002; Enomoto et al., 2003; Guan and Yamagata, 2003; Ding and Wang, 2005). Note that the wave trains accumulated energy over the South of the Yangtze River (Figure 5C), which enhanced the energy disturbance in the upper troposphere, thus reinforced the geopotential height anomaly over this area (Figure 2C). These results imply that there was an equivalent barotropic feature in the anomalous anticyclone over eastern China, and the intensified geopotential height in upper troposphere was conducive to uplifting the low-level geopotential height and enhancing anticyclonic circulation anomaly (Figure 2A). Therefore, the WPSH significantly extended westward (Figure 2B) comparing to its climate mean location, which was beneficial to the positive precipitation anomaly and the atypical rain belt orientation during the 2021 Meiyu period.

4 Conclusion and discussion

This study analyzed the abnormally high total precipitation over YHRV during the 2021 Meiyu period, and the causes of the unusual Northwest–Southeast oriented Meiyu rain belt by utilizing NCEP/NCAR daily reanalysis, CPC daily precipitation and COBE monthly SST data from 1979 to 2021. The conclusion are summarized as follows:

(1) The 2021 Meiyu period lasted from 10 June to 11 July, a total of 31 days. The precipitation in YHRV was above abnormal with the regional average total precipitation of 477.3 mm. The precipitation anomaly reached 188.0 mm, which was approximately 1.7 standard deviation. In 2021, there were two precipitation centers in YHRV, which were located at the junction of Anhui Province and Henan Province and the junction of Jiangsu Province, Anhui Province, and Jiangxi Province, respectively. Different from the zonal distribution of typical Meiyu precipitation anomaly, the Meiyu rain belt in 2021 was oriented from Northwest to Southeast.

(2) During the 2021 Meiyu period, the intensity of WPSH was weaker and extended further westward, causing a low-level cyclonic anomaly in the northwestern Pacific and an anomalous anticyclone in eastern China. In the east of Hainan Island, a positive vorticity anomaly was located in the lower troposphere, which stimulated the quasi-stationary wave trains propagating from this area to the northwestern Pacific through eastern China. The energy disturbance in eastern China and the northwestern Pacific generated low-level anticyclonic and cyclonic circulation anomalies in the above two areas, respectively. To some extent, the ZA, MA, and β terms contributed to the vorticity anomaly in the above two regions, but the contribution of the RWS term was the most prominent.

(3) The westward extension of WPSH was also associated with anomalous warming in the tropical Atlantic. During the 2021 Meiyu period, the positive SST anomaly in the tropical Atlantic led to anomalous convergence in the lower troposphere and anomalous divergence in the upper troposphere. The convergence anomaly in the upper troposphere over the eastern Mediterranean was caused by the monsoon-desert mechanism, which excited the quasi-stationary wave trains propagating downward along the mid-latitudes. Thus, the geopotential height in eastern China was intensified, which was favorable for the westward extension of WPSH.

(4) The WPSH weakened and extended further westward in the 2021 Meiyu season, which caused the anomalous easterly winds prevailed over the coastal areas of eastern China and southwesterly winds prevailed from Guangxi to the middle and lower reaches of the Yangtze River. And the airflows converged in YHRV. Similar transport and convergence anomalies existed in water vapor anomalies. The above-mentioned local circulation anomalies were jointly conducive to the positive anomaly of total precipitation in YHRV and the atypical spatial distribution of the Meiyu rain belt in 2021.

In addition to the weaker intensity and westward extension of WPSH during the 2021 Meiyu period, did the WPSH show similar characteristics in other years? If so, was the precipitation anomaly and its pattern in YHRV similar to those in the 2021 Meiyu period? The tropical Atlantic SST anomaly can stimulate the wave trains propagating downstream along the mid-latitudes in the Mediterranean through a monsoon-desert-like teleconnection, and thus affect the downstream climate anomaly. To further verify this mechanism, we plan to conduct several sets of sensitivity experiments related to the tropical Atlantic SST anomaly by using the atmospheric general circulation model in future studies. What are responsible for the weaker but westward extension of the WPSH in 2021? It is also worthy of further study.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

HL and GZ conceived and designed the study. HL, GZ, and ZM wrote the main manuscript text. All authors contributed to the discussion of the results and reviewed the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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