Climatic features of summertime baroclinic wave packets over Eurasia and the associated possible impacts on precipitation in southern China

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Funding information
China Meteorological Administration, Grant/Award Number: GYHY201406024; State Key Laboratory of Severe Weather of China, Grant/Award Number: 2015LASW-A03; Jiangsu Province

1 | INTRODUCTION

Southern China covers a vast area with complex terrain, where significant variations of summer precipitation occur with frequent droughts and floods. Due to the strong locality of precipitation, southern China is divided into a few sub-regions that have different variation features of precipitation (Chen et al., 2009; Zhang et al., 2014; Jin et al., 2015). Based on interannual variability of summer precipitation, the entire China is divided into 21 sub-regions using the rotated empirical orthogonal function (REOF) method, among which six subregions are located to the east of the Tibetan Plateau and south of Mountain Qinling (Jin et al., 2015). As interannual and interdecadal precipitation variabilities of summer precipitation in southern China are quite large (Li et al., 2016; Zhao et al., 2016), heavy precipitation events frequently occur in this region, leading to huge economic losses and casualties.

Precipitation in southern China, especially heavy persistent precipitation, is often related to westerly disturbances. The Rossby wave energy dispersion is one important reason that causes weather disturbances downstream. Previous studies have shown that activity of baroclinic wave packets over Eurasia in the summer of 1998 was more frequent and maintained longer than normal, which resulted in the accumulation of energy and provided a favorable background condition for the persistent heavy precipitation in the Yangtze River basin (Tan and Pan, 2002; Mei and Guan, 2009).
Mei and Guan (2008, 2009) proposed that the heavy persistent precipitation in the Yangtzi-Huai River valley during the Meiyu season was attributed to the influence of the Rossby wave packet (RWP), which originated from the Caspian Sea and propagated to southeastern China in 3–4 days.

In fact, the RWPs play a crucial role in weather system development in downstream region. Since the pioneering works by Yeh in 1949, and by Pedlosky in 1972 (Pedlosky, 1972), many studies have investigated features of the RWP including its spatial structure and propagation (e.g., Martius et al., 2008; Torn and Hakim, 2015; Wolf and Wirth, 2017). RWPs are potential vorticity-related and under influences of waveguide and storm-track (Chang, 1999; Martius et al., 2010; Chang et al., 2002; Hakim, 2003; Grazzini and Vitart, 2014). The group velocity of the Rossby waves is usually larger than the phase velocity for baroclinic RWPs (Yeh, 1949; Chang, 1993; Souders et al., 2014; Keller, 2017). Chang and Yu (1999) and Chang (1999) conducted in-depth study of wave packet structure using time-lagged one-point correlation maps and time-longitude cross sections, suggesting that the wave packets exhibit downstream development as the eastward group velocity is much faster than the phase velocity. They also revealed that the group velocity is highly correlated with meridional wind speed at 200–400 hPa, while the phase velocity is closely correlated with meridional wind speed at 500–700 hPa. Souders et al. (2014) further investigated RWPs and demonstrated the climatic features of the zonal speed, intensity, centroid position of the RWPs in Eurasia, the Pacific region, the Atlantic region, and even in the southern hemisphere. They also suggested that RWPs in the northern hemisphere exhibits more distinct seasonal variability as compared to those in the southern hemisphere.

Although the RWPs have been studies in many literatures, the features of the wave packets and their relationships with rainfall in East China have not been investigated as much as we expect. Here, there are two questions must be raised:

1. What are the climatic features of baroclinic wave packets over Eurasia in the summer?
2. What are the possible relationships between precipitation anomaly in southern China and activities of baroclinic wave packets?

These two questions are discussed in the present article, which will be helpful for our better understanding the features of circulation changes in Eurasia and mechanisms of occurrences of extreme precipitation in southern China.

2 | DATA AND METHOD

Daily winds are extracted from global 2.5° × 2.5° National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis product for the period of 1979–2016 (Kanamitsu et al, 2002). Precipitation data are derived from daily precipitation observations collected at 2479 weather stations in China during 1979–2016. Anomalies and disturbances of individual variables are defined as daily deviations from their multi-year mean of summer climatology of 1979–2016 (38 years in total). Here, summer is defined as June and July for rainfall is mainly received in these 2 months in south China.

Wave packets are obtained following the approach of Zimin et al. (2003). Specifically, Fourier transform is applied to anomalous meridional wind$v_1$ first, yielding the Hilbert transform$v_\lambda$. Then, the inverse process is performed, yielding the inverse Hilbert transform$W$. Finally, the wave envelope parameter$Ve(\lambda, \phi)$for the wave packet, which varies with longitude$\lambda$and latitude$\phi$, is obtained for purpose of investigation in the present article.

Time-lagged one-point correlation analysis of$Ve$ is used to explore the propagation path of perturbation energy associated with precipitation in the Yangtze River basin.

3 | CHARACTERISTICS OF BAROCLINIC ROSSBY WAVE ACTIVITIES

3.1 | Zonal wavenumbers and their changes

To obtain the wave packet parameter$Ve$, we have to clarify the dominant zonal wave-number of the anomalous meridional wind at 300 hPa in mid-latitude in the northern hemisphere. Figure 1 shows the power spectral of meridional wind disturbances over zonal belt [27.5°-50°N] in the summers of 1979–2016. It is found in Figure 1 that wavenumbers 5–6 are dominant in mid-latitude westerly disturbances during the 38-year period while the wavenumber 6 occurs more frequently. Waves with wavenumbers 4 and 7 also appear in some years. Centered around the dominant wavenumber$k$, the method proposed by Zimin et al. (2003) is applied to obtain wave envelope function$Ve$for waves with wavenumbers$k−1, k, k+1$ in every summer for further analysis of characteristics of$Ve$. Note that the group waves with wavenumbers 5–7 are here focused on, which are different from those in Souders et al. (2014) who used the waves with wavenumbers 3–11 for getting the RWP parameters.

3.2 | Spatial distributions of occurrences of strongest wave packets

In order to further examine the features of wave packet activities, the$Ve$at 300 hPa is calculated for each day of June–July in each year in period from 1979–2016. Each$Ve$center stands for each wave packet. Out of the 61 daily$Ve$ distributions in each year, we select 1 day when$Ve$reaches its maximum. Then we have 38 cases in total in 38 years from 1979 to 2016. The values and locations of these$Ve$ centers for these 38 cases are recorded and plotted in Figure 2. It is found that the maximum values of wave packets in each individual years during the
38-year period all occur to the north of 45°N, and they are largely concentrated in the region from western Europe to the north of Alps. Large \( V_e \) centers are located in the upstream of the Black Sea and Caspian Sea, indicating that this area is a “reservoir” of wave energy, from where wave energy propagates downstream. Note that between 30°-120°E, maximum wave packet appears almost every other 10 longitudes and basically distributes along the wind belt near 60°N, where multi-year averaged zonal wind speed is 8 m/s. The maximum wave packet does not distribute along the westerly jet probably because disturbances are easy to develop along the polar vortex edge. It is noted that the RWPs are clearly observed in June–July over Eurasia (Figure 2). This is not in agreement with the results by Souders et al. (2014) who claimed that the RWPs are nearly nonexistent in the summer months in the northern Hemisphere. This inconsistency might be resulted from the different ways of calculating \( V_e \) from waves with different wavenumbers.

### 3.3 Structure of wave packets

The mean spatial structure of wave packets in the northern hemisphere needs to be examined during Meiyu/Baiu season. During summers in period of 1979–2016, there appears
at least one wave packet every day in Eurasia. By selecting the strongest wave packet case in study domain every day, we then have 2,318 wave packets in total in 38 years. To explore the spatial features of wave packets in meridional, we first do zonal averages of $V_e$ at 300 hPa over [180°W-180°E] and then artificially shift the latitudinal location where $V_e$ peaks for each of 2,318 cases to 60°N. Corresponding average of $V_e$ and location shift are also done to each of 2,318 wave packets at 500 and 850 hPa. The results are presented in Figure 3a. Shown in Figure 3b are similar to those in Figure 3a but for cases with $V_e$ averaged over zonal belt [27.5°-50°N] and zonal shift from the location where 300 hPa $V_e$ peaks to 5°E. It is seen from Figure 3a that the intensity of wave packets increases with height. The maximum wave packet locates at the reference latitude 60°N at 300 hPa, inclining a little northward with height increases. The width of the mean wave packet is found to be about 50° lat. in meridional direction. Similarly, the wave packet in
zonal direction inclines slightly westward with height increases. Its length looks to be about 130°lon. in zonal direction. These features of the wave packets exhibit typical natures of the baroclinic Rossby waves.

3.4 Propagation speed of the wave packet

The wave packet of baroclinic Rossby waves propagates and induces the weather systems to develop in downstream region. The group velocity including its magnitude and directions can be estimated by tracking the migrations of wave envelope $V_e$. In previous case studies (Mei and Guan, 2008, 2009), it is found that it took 3–4 days for a wave packet at 300 hPa to travel from the Caspian Sea to the middle and lower reaches of the Yangtze River valley. Here we estimate the moving speed of wave packets by tracking the geographical locations of maximum $V_e$ in summers during the 38-year period. As the cases of wave packets are too many, we here exhibit wave packet migrations in Figure 4 for just severe Meiyu/Baiu years including 1983, 1987, 1993, 1998, 2003, and 2016. In each of the selected years, only parts of all RWP events are selected, which are able to be tracked by identifying the maximum values of $V_e$ in each day of the 5 days over Eurasia. Those RWPs with life cycle shorter than 5 days over Eurasia are ignored. As shown in Figure 4, the wave packet propagation path varies from year to year, but it is always located to the north of 35°N and south of 65°N. The meridional propagation velocity can reach up to 6 latitudes per day, that is, about 7 m/s. In the zonal direction, the maximum $V_e$ can start to migrate from region around the Alps to the vicinity of Scandinavia and end in the area from eastern China to upper Yanske Mountains, traveling 125 longitudes in 5 days. That is, the zonal propagation velocity of the wave packet is about 32 m/s. The paths along which the wave packets at 300 hPa propagate from the Mediterranean are found to be the eastward, the southeastward, and the northeastward. This is different from the results in previous study by Chang and Yu (1999) who suggests that there exist only two pathways of wave packet propagation in the northern hemisphere.

FIGURE 4 Locations where the maximum $V_e$ at 300 hPa observes in June–July in years including 1983, 1987, 1993, 1998, 2003, and 2016. The numbers from 1 to 5 with a particular color respectively indicates the locations where the wave packet moves to from day 1 to day 5. Numbers with different colors stands for the wave packets with different intensities at day 1. The wave packet usually takes 5 days to propagate from region near 10°E eastward to region near 120°E. The tracks of the RWP migration are denoted by the arrows that connect end to end.
Wave packet activities can cause significant precipitation anomalies in the downstream region. However, in the present study, we do not want to analyze influences of each individual wave packet. Instead, we focus on the relationship between interannual variability of summer precipitation at various regions in southern China and seasonal mean wave packet activities in summer. Following the subdivision of Jin et al. (2015), southern China comprises of six subregions, including the middle and lower reaches of the Yangtze River (subregion-I), Guangdong-Guangxi (subregion-II), areas to the south of the Yangtze River (subregion-VIII), Jiangxi-Fujian (subregion-XII), Bay of Hangzhou (subregion-XVI), and Qiongzhou Strait (subregion-XX). Simultaneous correlations of time series of area-averaged precipitation in June–July over the 38-year period from 1979–2016 in each individual subregion with baroclinic wave envelope parameter Ve at 300 hPa in the northern hemisphere are calculated. Results are displayed in Figure 5.

Precipitation in most area of southern China is associated with upstream wave packet activities, indicating that the downstream weather systems are influenced by the upstream Rossby wave energy dispersions. It is clearly seen from Figure 5 that multiple-year summer precipitation in the middle and lower reaches of Yangtze River valley (subregion-I) is related to wave packet activities from northeastern Aral Sea to the west of Lake Balkhash.

**FIGURE 5** Simultaneous correlation (shaded contours) between June–July mean Ve of baroclinic wave packets at 300 hPa and time series of June–July mean precipitation averaged over various subregions (small red box) of southern China during 1979–2016. Areas where the values of correlation coefficients are at and above 90% level of confidence using a t test are stippled with black dots. Superimposed vectors are the T-N wave activity fluxes in 10 m$^2$/s$^2$ at 300 hPa. The bold vectors are the T-N fluxes at and above 95% level of confidence. The divergence of the T-N fluxes (10$^{-5}$ m/s$^2$) is contoured with brown solid iso-lines for positive values and green dashed iso-lines for negative values.
subregion-II (Guangdong-Guangxi) is under the influence of wave packet activities over the large area from the Alps to Ural Mountains. The precipitation in subregion-VIII that locates to the south of Yangtze River is positively correlated with wave packet activities from the Norwegian Sea to the east of Ural Mountains and from Tianshan to Bohai, but negatively correlated with wave packet activities from Lake Baikal to Outer Hinggan Range. Precipitation in subregion-XVI (the Bay of Hangzhou) is highly correlated with wave packet activities in southern Mediterranean and Altai Mountains. Summer precipitation in subregion-XX (Qiongzhou Strait) is highly correlated with wave packet activities from the Black Sea to the south of Lake Balkhash.

To further understand the possible influences of RWPs on the precipitation in different subregions in South China, the horizontal component of wave activity fluxes (WAFs) and their divergences (Takaya and Nakamura, 2001) are presented in Figure 5. It is found that the WAFs propagate all the way from the large Ve-precipitation correlation centers into the corresponding subregions where the WAFs converge. Takaya and Nakamura (2001) formulated that \( \frac{\partial M}{\partial t} = -\nabla \cdot (\mathbf{C}_U M + \mathbf{W}_T) + D_T \), where \( M \) is for enstrophy related quantity, \( \mathbf{C}_U \) for the wave phase speed along basic flow, \( \mathbf{W}_T \) for the WAPs of RWPs besides \( \mathbf{C}_U M \), and \( D_T \) for the residuals, suggesting that where the WAFs converge where the disturbances tend to maintain. Therefore, except over the subregion-XVI, the disturbances over other subregions in southern China tend to maintain and henceforth to facilitate the strong rainfall event to occur. That is to say, the RWPs in westerly at 300 hPa can affect the disturbances over South China, being in consistent with the \( Ve \)-rainfall correlations distributions. Note that over the subregion-XVI, the WAFs are marginally converge. The occurrences of strong precipitation anomalies may due to other factors including \( -\nabla \cdot (\mathbf{C}_U M) \) and \( D_T \).

5 | CONCLUSIONS

In the summers during 1979–2016, baroclinic Rossby waves in the northern hemisphere demonstrate the following features.

Waves with zonal wave-numbers 5 – 7 are dominant in the mid-latitudes of northern hemisphere. The width in meridional direction and length in zonal direction of the wave packet are about 50°lat. and 130°lon., respectively. The intensities of wave packets are stronger in upper than in lower troposphere. The wave packet inclines a little northward with height increases, suggesting that the waves are baroclinic.

Rossby Wave packets largely originate from Western Europe to the north of the Alps. Wave energy propagates downstream from this region. The wave packets may propagate eastward, or southeastward or northeastward. Zonal and meridional propagation velocities of the wave packet can be up to 32 and 7 m/s, respectively.

During the period 1979–2016, interannual variability of summertime precipitation in southern China is closely associated with baroclinic wave packet activities. Summer precipitation anomalies in 6 sub-regions in southern China are affected by wave packet activities in different regions. For example, precipitation in Guangdong-Guangxi is significantly influenced by wave packet activities in region from the Alps to Ural Mountains whereas precipitation in areas to the south of Yangtze River is positively correlated with wave packet activities to the north of the Black Sea and south of the Mediterranean. Precipitation in Fujian-Jiangxi is closely associated with wave packet activities from the Norwegian Sea to the east of Ural Mountains and from Tianshan to Bohai and from Lake Baikal to Outer Hinggan Range. Summer precipitation in around Qiongzhou Strait is highly correlated with wave packet activities from the Black Sea to the south of Lake Balkhash.

Note that in the present study, only the climatic features of wave packet activities are explored, suggesting some relationships of precipitation anomalies in various areas of southern China with wave packet activities in different regions. However, the detailed impacts of a specific wave packet activity on precipitation are not deeply discussed in detail in the present study, and this issue may be addressed in the future.

ACKNOWLEDGEMENTS

This work is jointly supported by the China Meteorological Administration Special Public Welfare Research Fund (GYHY201406024), Creative Program of the State Key Laboratory of Severe Weather (2015LASW-A03), and PAPD project of Jiangsu Province. Precipitation data are from the archives in National Meteorological Information Center. The NCEP/NCAR reanalysis products are provided by NOAA CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov). All figures in the paper are produced using NCL (NCAR Command Language).

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How to cite this article: Ye D, Guan Z, Jin D. Climatic features of summertime baroclinic wave packets over Eurasia and the associated possible impacts on precipitation in southern China. Atmos Sci Lett. 2019; 20:e889. https://doi.org/10.1002/asl.889