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Relationship between the Late Spring NAO and Summer Extreme Precipitation Frequency in the Middle and Lower Reaches of the Yangtze River

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Abstract The relationship between the late spring North Atlantic Oscillation (NAO) and the summer extreme precipitation frequency (EPF) in the middle and lower reaches of the Yangtze River Valley (MLYRV) is examined using an NECP/NCAR reanalysis dataset and daily precipitation data from 74 stations in the MLYRV. The results show a significant negative correlation between the May NAO index and the EPF over the MLYRV in the subsequent summer. In positive EPF index years, the East Asian westerly jet shifts farther southward, and two blocking high positive anomalies appear over the Sea of Okhotsk and the Ural Mountains. These anomalies are favorable to the cold air from the mid-high latitudes invading the Yangtze River Valley (YRV). The moisture convergence and the ascending motion dominate the MLYRV. The above patterns are reversed in negative EPF index years. A wave train pattern that originates from the North Atlantic extends eastward to the Mediterranean and then moves to the Tibetan Plateau and from there to the YRV, which is an important link in the May NAO and the summer extreme precipitation in the MLYRV. The wave train may be aroused by the tripole pattern of the SST, which can explain why the May NAO affects the summer EPF in the MLYRV.

Keywords: North Atlantic Oscillation, summer extreme precipitation frequency, the middle and lower reaches of the Yangtze River Valley, East Asian westerly jet

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1 Introduction

The North Atlantic Oscillation (NAO), which governs large changes in surface temperature and precipitation over the Northern Hemisphere, is a climatic phenomenon in the North Atlantic Ocean that tracks fluctuations in the difference in atmospheric pressure at sea level between the Icelandic Low and the Azores High (Hurrell, 1995). Previous studies have shown that the NAO has a significant impact on the East Asian summer monsoon precipitation. In addition, the dominant spatial pattern of the summer rainfall variation is closely correlated with the NAO (Liu and Hou, 1999). Correlation analysis shows that the pattern of precipitation anomalies in the eastern Tibetan Plateau is closely associated with the NAO (Liu and Yin, 2001). The Meiyu onset date is significantly related to the atmospheric features in the previous winter, with a strong NAO for the early Meiyu onset and vice versa (Xu et al., 2001). The March NAO is closely related to the first leading precipitation mode, which exhibits an out-of-phase variation of the precipitation between the Yangtze River Valley and Southeast China. The January NAO is closely related to the third leading precipitation mode, which depicts the anomalous rainfall in North China and its out-of-phase variation in the Yangtze River Delta (Gu et al., 2009). An analysis of weather station data shows significant correlations between the December NAO index and precipitation over Korea and China in the subsequent summer (Sung et al., 2006).

In recent years, changes in the frequency and intensity of extreme climatic events have greatly impacted the ecosystem and China's economy. In this paper, we focus on the relationship between the May NAO and the summer extreme precipitation frequency (EPF) in the middle and lower reaches of the Yangtze River (MLYRV). The atmospheric circulation and humidity anomalies are associated with the positive anomalies in May NAO and the EPF in the MLYRV, and a possible linking mechanism is discussed.

2 Data resources

The study period in this paper is 1961–2009. The station precipitation dataset used in this study covers 74 stations in the MLYRV. This dataset was provided by the National Meteorological Information Center, China Meteorological Administration. Monthly mean atmospheric datasets from the National Center for Environmental Prediction and National Centers for Atmospheric Research (NCEP/NCAR) and reanalysis datasets with a 2.5°×2.5° horizontal resolution are also used. Extended reconstructed sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration are also used. All the above data are averaged for the summer months (June, July, and August, or JJA).

In this study, if the daily rainfall at a particular station exceeded the threshold value at the 95th percentile, as defined by the most popular international percentile

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method, the day was recorded as an extreme precipitation event. The EPF refers to the number of days at a given station characterized by extreme precipitation. The EPF index refers to the detrended and normalized EPF in JJA over the MLYRV.

The monthly index of the NAO is based on the difference of normalized sea level pressures between Ponta Delgada, Azores, and Stykkisholmur/Reykjavik, Iceland (Hurrell, 1995). In addition to subtracting the ENSO effect, the Niño 3.4 index is used in this paper (Trenberth, 1997).

3 Results

3.1 The statistical relation between the EPF and the May NAO

Table 1 shows the statistical relation between the EPF index and the monthly NAO index. Here, the two indexes are detrended and normalized. Correlation analysis shows that the JJA EPF in the MLYRV is closely associated with the May NAO. The correlation coefficient between the JJA EPF and the May NAO is –0.377 and is significant above the 99% confidence level, but the statistical relations between them in other months are not significant. The correlation coefficient between the JJA EPF and the May NAO is –0.332 and is significant above the 95% confidence level after excluding the ENSO signal. This result shows that the ENSO has a weak effect on the EPF in JJA over the MLYRV.

To further investigate this relationship between the summer EPF in the MLYRV and the May NAO, we consider the sea level pressure in May in association with the JJA EPF. The distribution of the sea level pressures in the May anomalies corresponding to a one-standard-deviation positive EPF index is shown in Fig. 1. There is a dipole pattern in the North Atlantic Ocean. The positive anomalies are found near the Arctic pole, and the negative anomalies appear over the Azores. This pattern, which shows a negative NAO phase, indicates the significant negative correlation between the May NAO and the JJA EPF in the MLYRV.

3.2 The atmospheric circulation anomalies

To confirm the possible mechanisms linking the JJA EPF in the MLYRV and the May NAO index, we first analyze the atmospheric circulation anomalies over the mid-high latitudes, which affect the EPF in summer over the MLYRV. The distribution of the JJA horizontal wind anomalies at 850 hPa, corresponding to a one-standard-deviation positive EPF index, is shown in Fig. 2a. There are two anticyclone anomalies, one over the Sea of Okhotsk and one over the Ural Mountains, indicating that two blocking high positive anomalies appear over the mid-high latitudes. In this pattern, the cold air from the mid-high latitudes invades persistently into the Yangtze River Valley (YRV). Consequently, the cold and warm air converge over the YRV, which favors abundant rainfall. Moreover, an anticyclone anomaly appears over the western North Pacific, which indicates that the western North Pacific Subtropical High (WNPSH) shifts farther westward. Figure 2b shows the regression coefficients of horizontal wind at 850 hPa on the May NAO index. Cyclone anomalies appear over the Sea of Okhotsk and the Ural Mountains, but these anomalies are not significant (not exceeding the 90% level). In the positive May NAO years, two blocking high anomalies become weaker than those in normal years. In addition, the western North Pacific is dominated by the cyclone anomaly, which is accompanied by the eastward WNPSH. These patterns are the opposite of the atmospheric circulation anomalies in the positive EPF index years. These results indicate a negative correlation between the JJA EPF in the MLYRV and the May NAO.

Figures 2c and 2d show the regressed patterns of the JJA zonal wind at 200 hPa on the EPF index and the May NAO index. In Fig. 2c, the westerly anomalies dominate the YRV, and the East Asian westerly jet core is located south of 35°N, which indicates that the jet moves dramatically southward. In Fig. 2d, the East Asian westerly jet core is located north of 45°N, and the westerly jet shifts northward. Therefore, a positive NAO in May tends to decrease the extreme precipitation in summer over the MLYRV. Previous studies have shown that the East Asian westerly jet plays an important role as a link between the East Asian summer monsoon precipitation and the NAO. During the years with a high NAO index, there is an inverse pattern of summer precipitation anomalies due to weakened upstream midlatitude westerly winds (Liu and Yin, 2001). When the jet stream moves to the north, the rainfall band moves poleward, which leads to a drier condition over the YRV and a wetter condition in northern China (Gong et al., 2002). When the summer rainfall is

Table 1 Correlation coefficients of the EPF index and NAO index during 1961–2009.

	Jan	Feb	Mar	Apr	May	Jun
NAO, EPF	0.011	0.187	–0.194	0.123	–0.377**	0.075
NAO, EPF (ENSO signals removed)	0.023	0.213	–0.196	0.071	–0.332*	0.07
	Jul	Aug	Sep	Oct	Nov	Dec
NAO, EPF	0.126	0.092	0.171	0.067	–0.187	0.081
NAO, EPF (ENSO signals removed)	0.124	0.086	0.163	0.054	–0.180	0.082

** Significant at the 99% confidence level; * significant at the 95% confidence level

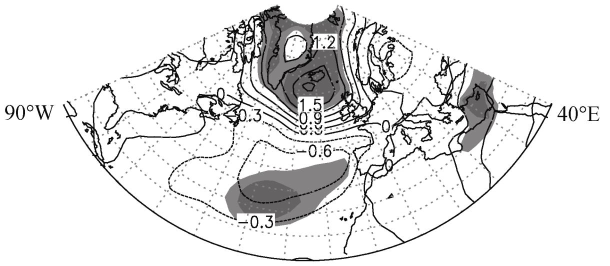

Figure 1 Regression coefficients of sea level pressure in May on the EPF index. Light and dark shading indicate the 90% and 95% confidence levels, respectively (Units: hPa).

above normal in the Yangtze River valley, strong westerly anomalies appear from the Yangtze River valley to Korea and Japan, and easterly anomalies appear over approximately 40–50°N (Zhou and Wang, 2006).

3.3 The anomalies of the humidity conditions over the MLYRV

Abundant water vapor is an important factor for precipitation, and the anomalous convergence of water vapor is beneficial for more rainfall. Figure 3a depicts the regression coefficients of the summer vertical integral (1000 hPa to 300 hPa) of the divergence of moisture flux upon the EPF index. The positive anomaly dominates the western North Pacific, and the negative anomaly appears over the MLYRV. These patterns indicate that the moisture divergence over the western North Pacific and the convergence over the MLYRV are associated with more extreme precipitation in summer over the MLYRV. A strong convergence pattern in the lower layer is associated with the development of convection. Figure 3b shows the regression coefficients of summer vertical velocity averaged along 90°E to 120°E on the EPF index. In the years with a positive EPF index, a strong ascending motion dominates over the MLYRV.

During the years of a positive May NAO index, a moisture divergence anomaly appears over the MLYRV (see Fig. 3c), and an anomalous sinking motion dominates the YRV (see Fig. 3d). Such patterns are favorable for less extreme rainfall in the MLYRV. Therefore, the May NAO has a negative effect on the humidity conditions over the MLYRV.

3.4 The bridge between the May NAO and the EPF in summer over the MLYRV

What is the bridge between the May NAO and the EPF in summer over the MLYRV? To answer this question, we investigate the wave train between the North Atlantic and East Asia. Figure 4 shows the regression coefficients of meridional wind at 200 hPa in JJA on the EPF index and on the May NAO index. Figure 4a clearly reveals a wave train-like pattern that seems to originate from the North Atlantic and then propagate southeastward to East Asia. Figure 4b also shows a wave train pattern that spreads northeastward to the high level of the YRV. Therefore, the wave train from the North Atlantic, extending eastward to the Mediterranean, the Tibetan Plateau and further continuing to the Yangtze River, is the major bridge between the NAO and the summer extreme precipitation in the MLYRV. The north-south variability of the zonal mean westerly anomaly results from the interaction between the eddy-driven anomalous stationary waves with NAO anomalies (Luo et al., 2007). Recent studies have dealt with the wave train between the North Atlantic and East Asia. The summer NAO signal is transported eastward to East Asia by a zonally oriented quasi-stationary barotropic Rossby wave train along the Asian upper-level jet, resulting in an anomalous summer air temperature over East Asia (Sun et al., 2008). Two cross-Eurasia wave trains, which are generated in the North Atlantic storm track, travel toward Asia via either the Scandinavia-Tibe-

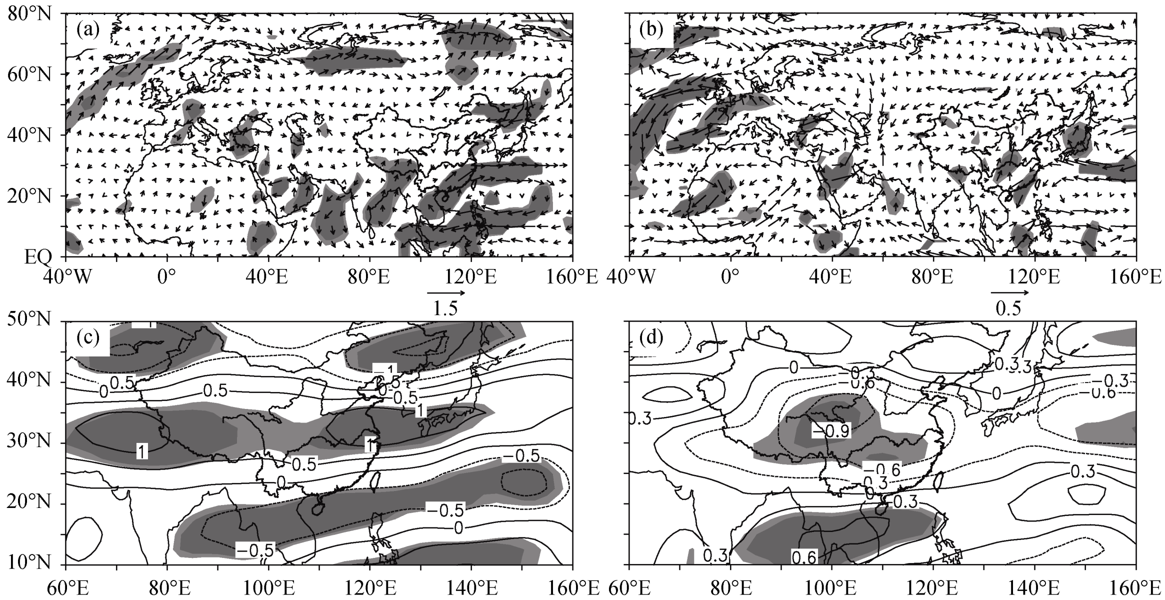

Figure 2 Regression coefficients of horizontal wind at 850 hPa and the 200-hPa zonal wind in JJA (a, c) on the EPF index and (b, d) on the May NAO index. Light and dark shading indicate the 90% and 95% confidence levels, respectively (Units: m s^{-1}).

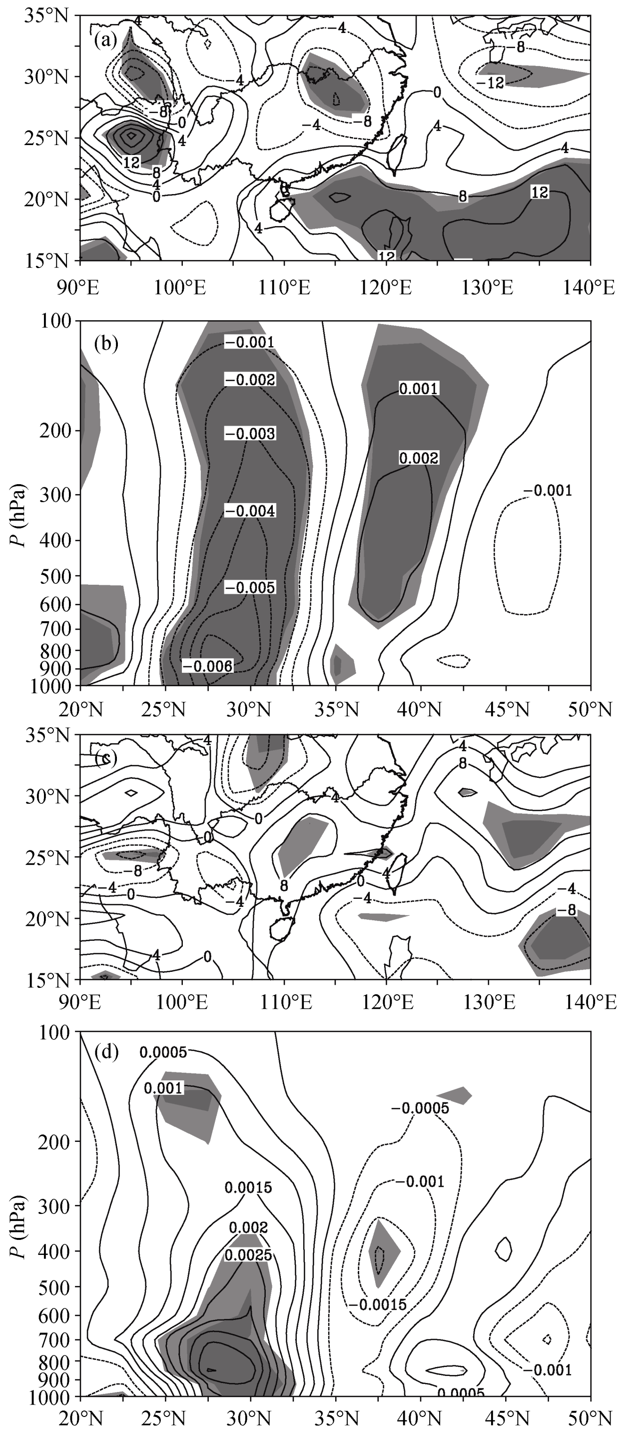

Figure 3 Regression coefficients of summer vertical integral (1000 hPa to 300 hPa) of divergence of moisture flux and vertical velocity averaged along 90°E to 120°E (a, b) on the EPF index (Units: Pa s^{-1}) and (c, d) on the May NAO index (Units: 10^{-6} kg m^{-2} s^{-1}). Light and dark shading indicate the 90% and 95% confidence levels, respectively.

tan Plateau bridge or the Mediterranean-East Asia bridge. It has been determined that these wave trains influence the occurrence of severe and extreme dryness and wetness on the Tibetan Plateau by modulating the local atmospheric circulation (Zhu et al., 2011). Significant correlations between the December NAO index and precipitation over Korea and China in the subsequent summer may be

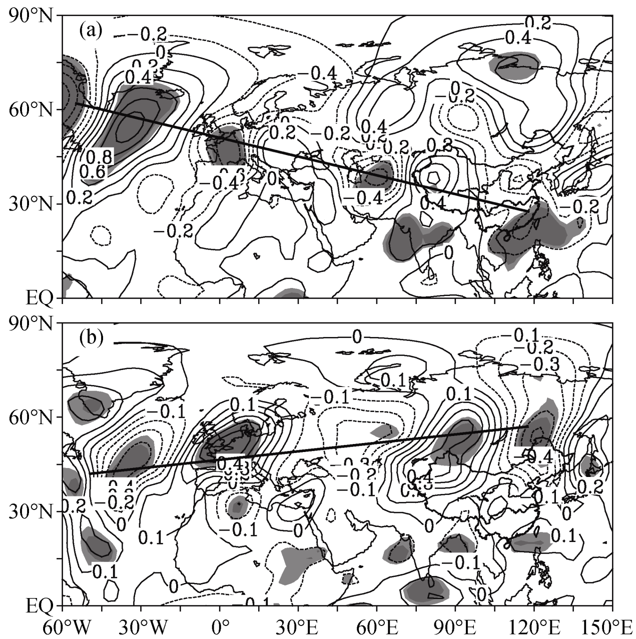

Figure 4 Regression coefficients of meridional wind at 200 hPa in JJA (a) on the EPF index and (b) on the May NAO index. Light and dark shading indicate the 90% and 95% confidence levels, respectively (Units: m s^{-1}). The black line denotes the wave train.

related to a wave train pattern that originates from the North Atlantic (Sung et al., 2006). The downstream extension of the NAO is caused by quasi-stationary Rossby waves trapped on the Asian jet waveguide and excited by a vorticity source associated with the NAO (Watanabe, 2004).

How does the May NAO excite such a wave train pattern in summer? Figure 5a shows the regression coefficients of the SST in May on the May NAO index. The tripole pattern of the SST appears in the North Atlantic, which reveals the close relationship between this tripole pattern and the NAO. To study the effect of the tripole pattern of SST on the May NAO, the tripole pattern of SST index (TSI) is defined by the difference of the average SST in May between the area of the positive correlation in the midlatitudes and the areas of the negative correlation in the high and low latitudes in Fig. 5a. The average SSTA fields in the North Atlantic include the curvilinear rectangle (50–54°N, 22–36°W; 32–36°N, 40–60°W; 14–24°N, 20–38°W) of Fig. 5a. The SSTA index successfully depicts the SSTA distribution in May over the North Atlantic. Figure 5b shows the regressed pattern of the JJA SSTA on the TSI. The tripole pattern of SST can persist from May to the subsequent summer. Figure 5c shows the meridional wind at 200 hPa on the TSI. The wave train also appears between the North Atlantic and East Asia. Therefore, this wave train may be aroused by the tripole pattern of SST, which can explain why the May NAO affects the summer EPF in the MLYRV. The "forcing" SST pattern projects significantly onto the tripole pattern generated by the NAO, which indicates a positive feedback between the SST tripole and the NAO (Czaja and Frankignoul, 2002). The effect of the spring

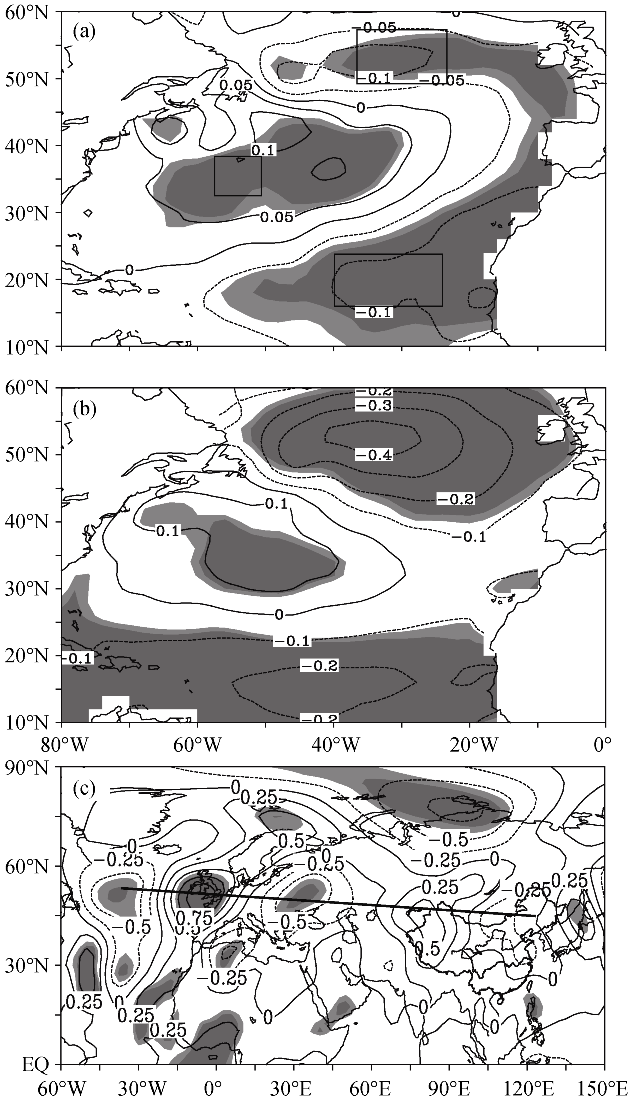

Figure 5 (a) Regression coefficients of SST in May on the May NAO index, (b) SST in JJA on the TSI and (c) meridional wind at 200 hPa in JJA on the TSI. Light and dark shading indicate the 90% and 95% confidence levels, respectively. The black line represents the wave train.

NAO on the annual variability of EASM depends on the persistence of the SSTA tripole pattern induced by the spring NAO itself (Wu et al., 2009; Zuo et al., 2012).

4 Summary and discussion

There are significantly negative correlations between the May NAO index and the EPF over the MLYRV in the subsequent summer. In positive EPF index years, there are two anticyclone anomalies situated over the Sea of Okhotsk and the Ural Mountains, which indicates that two blocking high positive anomalies appear over the mid-high latitudes. Such patterns are favorable to the cold air from the mid-high latitudes invading persistently into the YRV. Moisture convergence and the ascending motion appear in the MLYRV, which are favorable to increased rainfall in the MLYRV. The East Asian westerly jet core is located south of 35°N, and the East Asian westerly jet moves dramatically southward. In the positive May NAO years, the above patterns are reversed.

A wave train pattern that originates from the North Atlantic and extends eastward to the Mediterranean, the Tibetan Plateau and further reaches the Yangtze River plays an important role in linking the May NAO and the summer EPF. The wave train pattern may be aroused by the tripole pattern of SST, which can explain why the May NAO affects the summer EPF in the MLYRV. In association with the positive (negative) NAO in May, the signal is propagated eastward by a Rossby wave train along the northward (southward) westerly jet. The displacement of the WNPSH may correspond to the displacement of the East Asian jet (Lin and Lu, 2005). The northward (southward) WNSPH is unfavorable (favorable) for the moisture divergence (convergence) over the MLYRV, which is generally associated with less (more) extreme rainfall over the MLYRV.

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