NOTES AND CORRESPONDENCE

Record-Breaking Northward Shift of the Western North Pacific Subtropical High in July 2018

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Abstract

The northward shift of the Western North Pacific Subtropical High (WNPSH) in July 2018 broke the historical record since 1958 and resulted in extreme heat waves and casualties across Northeast Asia (NEA). In the present work, we associated this extreme WNPSH anomaly with the anomalies of barotropic anticyclone above NEA originating from the strongest positive tripole pattern of sea surface temperature anomaly (SSTA) in the North Atlantic in July. Both data analysis and numerical experiments indicated that the positive tripole SSTA pattern could produce an upper-tropospheric wave source over Europe, which stimulated an eastward propagating wave train along the subpolar westerly jet over the Eurasian Continent. When its anticyclonic node reached NEA, the WNPSH started to shift northward. After the cyclonic node in the circulation anomaly encountered the Tibetan Plateau (TP), atmospheric diabatic heating was enhanced over the eastern TP, initiating another subtropical wave train, which furthered the northward shift of the WNPSH. Therefore, the wave source over Europe was critical for the northward shift of the WNPSH in July, connecting the tripole SSTA pattern in the North Atlantic with the WNPSH anomaly and maintaining the downstream effects of thermal forcing over the eastern TP on the East Asian summer monsoon.

Keywords western North Pacific Subtropical High; Tibetan Plateau; North Atlantic; tripole sea surface temperature anomaly

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1. Introduction

The lower-tropospheric subtropical anticyclone over the North Pacific covers approximately 20–25 % of the Northern Hemisphere. Its portion over the western Pacific, usually termed the Western North Pacific Subtropical High (WNPSH), is an important component in the East Asian summer monsoon (EASM) (Lau and Li 1984; Tao and Chen 1987; Huang and Li 1992; Liu and Wu 2004). Climatologically, the WNPSH jumped poleward to the north of 20°N in early June following the Mei-yu-Baiu-Changma rainy season and continued to the north of 30°N in mid–late July following the rainy season over Northeast Asia (NEA). The meridional movement of the WNPSH not only determined the position of the EASM rainy belt (Ninomiya and Kobayashi 1999; Lu 2002; Zhou and Yu 2005) but also caused heat waves in the affected regions, especially over East China and Southern Japan (Enomoto et al. 2003; Ding et al. 2010; Chen and Lu 2015; Wang et al. 2015; Kueh et al. 2017). Thus, the meridional position of the WNPSH has been widely considered in the seasonal prediction of the EASM (Wang et al. 2013; Yim et al. 2016).

Previous studies ascribed the anomalies of the WNPSH in boreal summer to two distinct atmospheric teleconnection patterns. One anomaly is the Pacific–Japan or East Asia–Pacific teleconnection originating from the anomalous tropical convection over the western Pacific (Huang and Li 1987; Nitta 1987), and the other includes the zonally distributed anomalies of circulation over the Eurasian Continent, termed the “Silk Road” wave pattern or the Atlantic–Eurasian (AEA) teleconnection (Enomoto et al. 2003; Li and Ruan 2018). The former anomaly was significantly modulated by the El Niño–Southern Oscillation (ENSO) and the sea surface temperature anomalies (SSTAs) in the tropical Indian and western Pacific Ocean (Zhang et al. 1996; Wang et al. 2000; Sui et al. 2007; Yang et al. 2007; Liu et al. 2018), whose physical processes have been reviewed recently (Xie et al. 2016; Li et al. 2017). The latter anomaly, however, was ascribed to the atmospheric internal variability (Ding and Wang 2005; Sato and Takahashi 2006; Kosaka et al. 2012). The combination of these two teleconnections could deeply affect the WNPSH and produce extreme climate disasters over East Asia (Orsolini et al. 2015; Wang and He 2015; Wang and Wang 2018; Wang et al. 2018a).

In July 2018, a series of extreme heat waves occurred over NEA, including Japan, the Korean Peninsula, and Northeast China. Meanwhile, some extensive heat waves attacked Europe, the Arctic, and North America. These extreme heat waves killed more than 80 people in Japan and resulted in unprecedented wildfires in Northern Europe. However, the circulation anomalies associated with these extreme events have not yet been clearly addressed. Considering the close association between the WNPSH and the heat waves over East Asia, the aim of the present work is to examine the circulation anomalies related to the WNPSH and their possible causes in July 2018.

2. Data and methods

We used the Japanese 55-year Reanalysis (JRA-55) dataset from 1958 to 2018 with a horizontal resolution of 1.25° × 1.25°, which was released by the Japan Meteorological Agency (JMA) (Kobayashi et al. 2015; Harada et al. 2016). The variables included the sea level pressure (SLP) and the surface air temperature (SAT) near the surface, as well as the three-dimensional air temperature, geopotential height, components of the diabatic heating rate, and wind fields on 27 standard isobaric surfaces from 1,000 to 100 hPa. Here the diabatic heating rate was the sum of the convective, large-scale condensation, long- and short-wave radiative, and vertical diffusion flux heating rates. The SAT in this reanalysis showed a significant correlation with the in situ observations over NEA provided by the National Meteorological Information Center of the China Meteorological Administration. The sea surface temperature (SST) was derived from the JMA Centennial in situ Observation-Based Estimates (COBE) SST dataset as an input for the JRA-55 reanalysis (Ishii et al. 2005).

The anomaly of each meteorological element was obtained by subtracting the climatological value during the period from 1981 to 2010 from the original. Two types of numerical experiments were conducted to validate the data analysis results. One was an ideal linear baroclinic model (LBM) with a T42 resolution in the horizontal direction and 20 sigma levels in the vertical direction (Watanabe and Kimoto 2000). The other was an atmospheric general circulation model (AGCM) of the global Community Atmosphere Model, Version 5.1 (CAM5), whose horizontal and vertical resolution were 1.9° × 2.5° finite volume grid and 27 hybrid sigma pressure levels, respectively (Worley and Drake 2005). The design of the numerical experiments is specified in Section 4.

3. Extreme northward shift of the WNPSH in July 2018

The record-breaking temperatures in July 2018
over NEA accompanied the extreme northward shift of the WNPSH (Fig. 1). The northern edge of the WNPSH at 500 hPa reached 40°N in July 2018, which broke the 1958–2017 historical record. In the upper troposphere, the South Asian High (SAH) clearly expands northeastward onto NEA (Fig. 1a). In the lower troposphere, the WNPSH intrudes northwestward onto NEA, and a deeper monsoon trough settles in the western North Pacific (WNP) (Fig. 1c). The extreme northward shift of the WNPSH presents an anticyclonic anomaly with a barotropic structure over NEA, along with the anomalies of baroclinic circulation over the WNP, including the low-level cyclonic and upper-level anticyclonic anomaly south of 30°N. Accordingly, the atmospheric ascending is enhanced over the WNP, but the stronger atmospheric sinking occurs in the troposphere over NEA (Figs. 1d–f). As shown by the pentad evolution (Figures not shown),...
this anomaly of the meridional circulation becomes well organized to form a closed cell in mid-July, when the tropical convection gets enhanced over the WNP, indicating the tropical influence on the local meridional circulation over East Asia in July 2018.

The enhanced atmospheric ascending and sinking over East Asia in July 2018 are associated with anomalous vertical motion and SSTAs (Fig. 2a). The large-scale ascending anomalies are centered over the WNP, whereas the anomalous sinking is located over the tropical Indian Ocean and subtropical Atlantic. Meanwhile, the anomalous diabatic heating increases over the tropical western Pacific, but the anomalous cooling strengthens over the tropical Indian Ocean (Figs. 2b, c). In the tropics, the anomalous diabatic heating and cooling are primarily induced by the anomalies of deep convection. The wavenumber-one structure in the anomaly of the large-scale divergence is associated with the deeper convection in the Madden–Julian Oscillation (MJO), which arrives at the WNP and the Maritime Continent in July 2018 (Figure not shown). Warmer SSTAs are seen in the tropical western Pacific and Indian Ocean. In contrast, a tripole SSTA pattern is observed in the North Atlantic, exhibiting a warm SSTA in the middle latitude sandwiched by colder SSTAs in the subtropical and higher latitudes. The extreme northward shift of the subtropical anticyclone occurs throughout the troposphere of East Asia, corresponding to the uniform distribution of warmer air over NEA from the surface to 200 hPa (Fig. 2b). Such a distribution of circulation anomalies and SSTAs indicates that the SSTAs act as the external forcing of the atmosphere over the tropical WNP and subtropical Atlantic Ocean, whereas they act as a response to the atmospheric forcing in the tropical Indian Ocean. Due to the fact that the monthly

Fig. 2. (a) Horizontal distribution of the SSTA (shading, °C), anomalies of velocity potential (contours, 10^6 m^2 s^{-1}), and divergent winds (m s^{-1}) at 150 hPa in July 2018; (b) 110–135°E averaged pressure–latitude cross section of anomalous diabatic heating (contours, K day^{-1}), meridional circulation (vectors, m s^{-1}), and air temperature (shading, K) in July 2018 (bold black and blue lines in (b) are the ridge lines of the anticyclone in climatology and 2018, respectively); and (c) is similar to (b) but is the approximately 0–20°N averaged pressure–longitude cross-section. The vectors in (c) denote the anomalies of the zonal circulation. The light gray shading in (b) and (c) is the topography.
mean atmospheric anomalies are mainly maintained by external forcing (Hoskins 2013), we need to further examine the forcing effects of the two regional SSTAs on the extreme northward shift of the WNPSH in July 2018.

4. Possible causes of the extreme northward shift of the WNPSH

4.1 Diagnosis results

The mid–high-latitude wave train, which has been attributed to the tripole SSTA pattern in the North Atlantic (Li et al. 2008; Wu et al. 2009), is investigated using the wave activity flux (Takaya and Nakamura 2001). The climatological circulation in July is treated as the basic flow in this calculation. Two wave trains at 300 hPa were detected over the Eurasian Continent in July 2018 (Fig. 3a). The wave source manifesting as an extensive anticyclonic anomaly above Europe is located at 300 hPa north of 50°N. One wave train emerges between 50°N and 70°N, propagates eastward along the subpolar westerly jet to form a cyclonic node over Siberia, and then turns southeastward to produce an anticyclonic node over NEA. The other wave train emerges between 30°N and 40°N and propagates eastward along the subtropical westerly jet, as indicated by the anomalies of the anticyclone over the Caspian Sea, the cyclone over the western Tibetan Plateau (TP), and the anticyclone over NEA. The anomalies of the stream function over the WNP are much weaker in July (Figs. 3a, b). Although the stronger tropical convection accompanies the northward shift of the WNPSH in mid-July 2018, the WNPSH shifts northward faster in early and late July without the strengthened tropical convection over the WNP (Figure not shown). This indicates the weak influence of the tropical forcing in this case.

The vertical structures of the stream function and diabatic heating involved in these two wave trains are different. A pronounced barotropic structure of the stream function anomalies is observed in the mid–high-latitude wave train with respect to the warmer SAT and positive SLP anomalies over Europe and NEA (Figs. 3b, d). Based on the vertical vorticity equation derived from the Ertel potential vorticity equation (Wu and Liu 1998; Liu et al. 2004), the anomalous diabatic heating centered near the Caspian Sea and the Mongolian Plateau could result in the negative vorticity production above the layer with maximum heating. The midlatitudinal westerly wind then brings the anomalies of negative vorticity downstream to Central Asia and NEA, where the in situ anticyclonic anomaly is developed. Although the anticyclonic anomaly over NEA is still barotropic, corresponding to the subtropical wave train, the anomalies of the stream function surrounding the TP exhibit a baroclinic structure in the vertical direction. In particular, the anomaly of the upper-level anticyclone exists with the low-level cyclone over the eastern TP, possibly enhanced by the local atmospheric diabatic heating (Fig. 3c). The warmer SAT and negative SLP anomalies over the eastern TP suggest the influences of the TP thermal forcing on the northward shift of the WNPSH in July 2018 (Fig. 3b).

4.2 Statistical analysis

Actually, the extreme case in July 2018 follows the common relationship of the anticyclonic anomaly over NEA with the wave source over Europe, the diabatic heating over the eastern TP, and the tripole SSTA pattern in the North Atlantic during the past decades (1981–2017). Here, the tripole SSTA pattern is expressed as the 3rd empirical orthogonal function (EOF) mode of the SSTAs in the North Atlantic in July (Fig. 4a). Its intensity is measured by the third principle component (Fig. 4b). The 1st mode of the North Atlantic SSTA and its principle component indicates a unified warming trend in the basin, whereas the 2nd mode is featured by a meridional quadrupole pattern with apparent interdecadal variability of its time series (Figures not shown). These two modes have an insignificant correlation with the anticyclonic anomaly over NEA.

The anticyclonic anomaly over NEA is insignificantly negatively correlated with the anomaly of the atmospheric heat source over WNP, corresponding to the minor role of the tropical forcing (Table 1). In contrast, it is significantly positively correlated with the wave source over Europe, the diabatic heating over the eastern TP, and the intensity of the tripole SSTA pattern in the North Atlantic (Table 1). The partial correlation analysis shows their coefficients on the anticyclonic anomaly over NEA (Table 1). In the case without the wave source over Europe, the correlation of either the tripole SSTA pattern in the North Atlantic or the diabatic heating over the eastern TP becomes insignificant with the anticyclonic anomaly over NEA. If the diabatic heating over the eastern TP was removed, the downstream effect of the wave source over Europe would be weakened to some extent, whereas the influence of the tripole SSTA pattern would be insignificant. Excluding the tripole SSTA pattern, despite some reduction of the partial correlation coefficients, the anticyclonic anomaly over NEA is still significantly associated with both
the wave source over Europe and the diabatic heating over the eastern TP. These statistical relationships become more evident when including the case of 2018 with the maximum of the above elements since 1981, corresponding to the extreme northward shift of the WNPSH (Fig. 4b).

The statistical analysis suggests that the wave source over Europe and the thermal forcing over the eastern TP are two important factors for maintaining the influence of the tripole SSTA pattern in the North Atlantic on the northward shift of the WNPSH in July. Meanwhile, the effect of thermal forcing over the
eastern TP on the WNPSH also depends on the wave source over Europe. One possible reason is that the thermal forcing over the eastern TP could not affect the WNPSH unless the stronger westerly wind south of the anomalous cyclonic node in the mid–high-latitude wave train originating from this wave source encountered the high topography of the TP (Figs. 3a, 5b). Since the influence of thermal forcing over the eastern TP depends on the mid–high-latitude wave train, the correlation coefficients cannot separate the relative contribution by the two wave trains to the WNPSH, but they show their ccoects on the extreme northward shift of the WNPSH in July. The above processes will be verified using some numerical experiments.

### 4.3 Numerical experiments

#### a. LBM results

Using the LBM, we designed four sensitivity experiments to examine the atmospheric internal processes of the extreme northward shift of the WNPSH. Consistent with the observations, an anticyclonic anomaly is positioned at 300 hPa over Europe in the first experiment (EUR_EXP). In the second and third experiments, the diabatic heating presented by a reasonable vertical profile is positioned over the eastern TP (ETP_EXP) and WNP (WNP_EXP) (Fig. S1). The dynamic forcing in EUR_EXP and the thermal forcing in ETP_EXP are superposed together in the fourth experiment (EUR+ETP_EXP). The two distinct wave trains are generally reproduced by the EUR+ETP_EXP, and the simulated anticyclonic anomaly is remarkable in the upper troposphere of NEA (Fig. 5a). The pattern correlation coef-
Fig. 5.  (a) Steady responses of circulation to the total forcing of the upper-level wave source above Europe and diabatic heating over the eastern TP (EUR+ETP_EXP) represented by the anomalies of the stream function (contours, $10^6$ m$^2$ s$^{-1}$) and wave activity flux (vectors, m$^2$ s$^{-2}$) at 300 hPa.  (b), (c), and (d) are the responses of the 300-hPa stream function (contours, $10^6$ m$^2$ s$^{-1}$) to sole forcing of the (b) wave source over Europe (EUR_EXP), (c) diabatic heating over the eastern TP (ETP_EXP), and (d) the WNP (WNP_EXP), respectively.  Purple lines represent the 1500-m topography contours.  Shading in (a) is for the climate-mean westerly wind at 300 hPa in July (m s$^{-1}$).  Light gray shading in (b), (c), and (d) denotes the forcing position of the 300-hPa relative vorticity, 300-hPa diabatic heating over the eastern TP, and 500-hPa diabatic heating over the WNP in order.  In the LBM experiment, the mean climatic circulation in July is regarded as the basic flow.  Each experiment is integrated for 31 days, and the averaged results for the last 15 days are analyzed to demonstrate steady responses.
ficient (PCC) between the simulated and the observed circulation anomalies over NEA reaches 0.50, indicating that this experiment can capture the major features in observation. However, the discrepancy in the LBM experiment is that the simulated anticyclonic anomaly over NEA is weaker than the observation, owing to the lack of local feedback between circulation and the diabatic process. In reality, when the diabatic cooling is apparent over NEA, its corresponding descent could further enhance the in situ anticyclonic anomaly (Figs. 1c, 3c). When the LBM is solely forced by the wave source over Europe, the EUR_EXP produces only the mid–high-latitude wave train. The nodes of the anomalous stream function are distributed north of 40°N, and the anticyclonic anomaly over NEA is considerably weaker compared to that of the EUR+ETP_EXP (Figs. 5a, b). If the diabatic heating over the eastern TP is included, the ETP_EXP can duplicate the subtropical wave train, as indicated by the anomaly of the upper-tropospheric cyclone over the eastern TP and the anticyclone over the Mediterranean and NEA (Fig. 5c). The circulation simulated in the WNP_EXP, however, is dramatically different from the observations (Fig. 5d). Consequently, both the wave source over Europe and the thermal forcing of the eastern TP possibly led to the extreme northward shift of the WNPSH in July 2018. The LBM experiments indicate that the thermal forcing of the eastern TP exerts a direct influence on this shift.

b. AGCM results

The AGCM experiments are used to validate the influences of the tripole SSTA pattern in the North Atlantic. CAM5 is driven by the climatological COBE SST with a seasonal cycle and integrated for 15 model years to obtain the results of control run (CTL). In the sensitivity experiment (SEN), we attach the observed EOF-3 mode of SST in the North Atlantic in July 2018 to the climatological SST to generate the forcing field, and we integrate the AGCM based on the CTL outputs with the forcing field in the last 10 model years. The differences between SEN and CTL in these 10 years present the effects of the tripole SSTA pattern in the North Atlantic in July.

The CTL outputs can capture the major features of the WNPSH in July, except that the simulated WNPSH in the AGCM is wider in the meridional direction and stronger than the observation (Figs. 1b, 6a). This is probably due to the lack of air–sea interaction over the western Pacific warm pool (Wang et al. 2005; Kim and Hong 2010; Song and Zhou 2014; Jin and Stan 2016). When treating the PCC of 0.5 between the observed and the simulated anomalies of the stream function over the domain (30°–80°N, 60°W–150°E) as a threshold, 6 out of the 10 members can better reproduce the anomalies of circulation in July 2018. The PCC of the anomalous stream function between observation and simulation averaged using the six members reaches 0.72. These SEN outputs can reproduce the northward shift of the WNPSH under the influences of the positive tripole SSTA pattern in the North Atlantic (Fig. 6a). Meanwhile, the diabatic heating gets enhanced over the eastern TP in July (Figs. 6b, d). The extensive anomaly of upper-tropospheric anticyclone is simulated over Europe (Figs. 3a, 6c). Two wave trains are also stimulated as in the observation. One is along the subpolar westerly jet, whereas the other is along the subtropical westerly stream over the Eurasian Continent (Fig. 6c). The anticyclonic anomaly over NEA is embedded in these two wave trains to induce the northward shift of the WNPSH. The vertical structure of the northern wave train resembles the counterpart in observation (Figs. 6d, e). The anomaly of diabatic cooling is strong over NEA, corresponding to the local extreme high temperatures (Fig. 6d). Therefore, the AGCM experiments can verify the effect of the positive tripole SSTA pattern in the North Atlantic on the extreme northward shift of the WNPSH in July 2018. Although no tropical forcing is involved in the AGCM experiments, the model could still reproduce the observed anomalies of circulation. This confirms the weak influence of the tropical convection on the northward shift of the WNPSH in July 2018.

5. Summary and discussion

An extensive extreme heat wave affected NEA and caused many deaths in Japan in July 2018. The present work shows that these extreme heat waves were directly associated with the record-breaking northward shift of the WNPSH. This shift presented a very strong anomaly of the tropospheric anticyclone with a barotropic structure over NEA, which was induced by the strongest positive tripole SSTA pattern in the North Atlantic in July since 1981. The meridional gradient of the SSTA could strengthen the low-level convergence over the warm SSTA in the North Atlantic, where the anomalous diabatic heating took place with its center in the middle troposphere. Local negative vorticity production thus emerged in the upper troposphere because of the vertical gradient of this diabatic heating (Wu and Liu 1998). Under the influence of the upper-level westerly wind, this negative vorticity anomaly was advected onto Europe.
to form a wave source, leading to the northward shift of the WNPSH via two distinct wave trains over the Eurasian Continent. One wave train, located in the mid–high latitudes along the subpolar westerly jet, could produce the anticyclonic node over NEA and the cyclonic node over Siberia via a dynamic procedure. The anticyclonic node could directly induce the northward shift of the WNPSH. As the stronger westerly at the southern cyclonic node encountered the TP, the topographic uplifting would enhance the rainfall-related diabatic heating over the eastern TP to invoke another wave train in the subtropics. This wave train propagated eastward along the subtropical westerly jet, further strengthening the anticyclonic anomaly in the mid-upper troposphere of NEA. Owing to the barotropic structure of the midlatitudinal circu-

Fig. 6. Atmospheric response (SEN minus CTL) to the tripole SSTAs pattern in the North Atlantic in July 2018 in the AGCM experiments. (a–c) Horizontal distribution of (a) the 5900-gpm geopotential height at 500 hPa (black lines: CTL results, blue lines: SEN results); (b) the anomalies of diabatic heating at 300 hPa (K day$^{-1}$, values exceeding 90 % confidence level are stippled); and (c) the wave activity flux (vectors, m$^2$ s$^{-2}$) and anomalous stream function (contours, 10$^6$ m$^2$ s$^{-1}$) at 300 hPa (black lines are for the basic westerly flow starting from 5 m s$^{-1}$ interval by 10 m s$^{-1}$). Purple lines denote the 1500-m topography). Light grey shading in (a) and (c) are for the values passing the 90 % confidence level. (d–e) Vertical structure of anomalous diabatic heating (shading, K day$^{-1}$) and stream function (contours, 10$^6$ m$^2$ s$^{-1}$) averaged along (d) 35–42.5°N and (e) 45–55°N, respectively (gray shading represents the topography).
lation anomaly, the upper-level anticyclonic anomaly could result in in-phase anomalies of circulation in the lower troposphere of NEA, finally resulting in the record-breaking northward shift of the WNPSH in July 2018. However, the tropical convection associated with the MJO had a weak influence in this process.

The present study also shows the uncertainty in the influence of the tripole SSTA pattern in the North Atlantic on the northward shift of the WNPSH in July. The statistical analysis indicates that the wave source over Europe and the thermal forcing over the eastern TP could affect the northward shift of the WNPSH, even excluding the tripole SSTA pattern (Table 1). Meanwhile, four members in the AGCM experiment failed to reproduce the circulation anomaly over the Eurasian Continent. This implies that the downstream effect of the tripole SSTA pattern in the North Atlantic will be disturbed if either the wave source over Europe or the thermal forcing over the eastern TP is modulated by other factors. Thus, more works are required to investigate the reason behind this uncertainty, which may limit the climate predictability of the mid–high-latitude circulation.

The record-breaking northward shift of the WNPSH in July 2018 has deeply impacted human health over East Asia. One urgent issue is whether such an event will occur more frequently in the future. Some recent evidence showed that global warming has increased the frequency of extreme heat waves over East Asia and thus increased the health risk of more than 30% of the population worldwide (Otto 2016; Campbell et al. 2018; Chen et al. 2019; Wang et al. 2019). However, how global warming affects heat waves and the northward shift of the WNPSH is still unclear. As reported in the present work, the interaction between the two wave trains over the Eurasian Continent is embedded in the subpolar and subtropical westerly jet. It is possible that the long-term variation in the tropospheric thermal structure could affect the position and distribution of these two jets, further modulating the downstream effects of the wave source over Europe by changing the propagation of its resultant wave trains. More studies are needed to confirm the above hypothesis.

Supplements

Figure S1 shows (a) the horizontal distribution of relative vorticity forcing at 300 hPa over Europe in the EUR_EXP, (b) its vertical structure, and (c) the horizontal distribution of diabatic forcing at 500 hPa over the WNP in the WNP_EXP and the counterpart at 300 hPa over the eastern TP in the ETP_EXP. (d) and (e) denote the vertical profile of the diabatic forcing over the WNP and eastern TP domains, respectively.

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