Role of Large-Scale Circulation and Terrain in Causing Extreme Heat in Western North China

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ABSTRACT

Previous studies have suggested that, because of its particular location on the southeastern lee side of mountains, extreme heat (EH) over western north China (WNC) is affected by the foehn phenomenon. In this study, the EH days during summer over this region are categorized into foehn-favorable EH and no-foehn EH, according to whether there are anomalous northwesterlies over mountains, and composite analyses are performed on them. The analyzed results indicate that the no-foehn EH is characterized by an anticyclonic anomaly and a large-scale higher surface air temperature, while the foehn-favorable EH is featured by a cyclonic anomaly to the northeast and a localized higher temperature. Associated with the cyclonic anomaly, northwesterlies prevail over the mountain surface and provide a favorable environment for the occurrence of the foehn effect over WNC, which is located on the southeastern lee side of mountains. That is, both cyclonic and anticyclonic anomalies can induce EH over WNC (i.e., foehn-favorable EH and no-foehn EH, respectively). Further investigation indicates that large-scale cyclonic and anticyclonic anomalies tend to favor local descent and ascent anomalies over the lee side, respectively, through interaction with the particular terrain. Therefore, large-scale circulations and local terrain-induced winds play an offsetting role in affecting the surface air temperatures over WNC, and EH occurs when anomalous large-scale anticyclone or terrain-induced descent dominate. This study implies that attention should be paid to not only the upper-level/large-scale circulations but also to their impact on lower-level/local winds for temperature variability over the places with great topographic relief worldwide.

1. Introduction

The World Meteorological Organization (WMO) recently reported that the world has experienced the warmest decade in 2001–10 since instrumental global average surface temperature became available in 1850, increasing by 0.88°C since the first decade of the past century (1901–10) (WMO 2013). Meanwhile, extreme heat (EH) occurs more frequently and takes its toll on the people trapped in it (Vanhees et al. 2003; Tan et al. 2007; Robine et al. 2008; Corobov et al. 2013). The total deaths due to EH dramatically enhanced by more than 2000%, from less than 6000 in 1991–2000 to more than 136000 in 2001–10 (still 800% after excluding the European mega–heat wave of 2003, which eased ~70 000 deaths, and the Russian heat wave of 2010, which caused ~11 000 deaths), markedly larger than an overall increase of 20% due to various extreme climate conditions, including heat, cold, drought, storms, and floods (WMO 2013). Moreover, the economic losses owing to EH noticeably increased by 136% during the same period, including crop failures, forest fires, and overwhelming water and electricity shortages (Peng et al. 2004; He et al. 2008; Coumou and Rahmstorf 2012; WMO 2013). The destructive impact of EH calls for a comprehensive understanding of the mechanisms responsible for its occurrence.
Regional features should be taken into consideration to specify the general circulation associated with EH in different areas (Garcia-Herrera et al. 2005; Loikith and Broccoli 2012; Chen and Lu 2015). For instance, Loikith and Broccoli (2012) sought the circulation patterns associated with EH over North America and indicated that the pattern differs obviously from the typical anticyclonic pattern for EH over the extreme southern extent of the domain (i.e., mainly over Mexico). A similar situation takes place in China. Chen and Lu (2015) systematically compared the circulation anomalies associated with EH in different regions of eastern China and revealed that the circulation in western north China (WNC) is uniquely influenced by the underlying topographies, with the Taihang Mountains along the southwest–northeast orientation to the west, and the Yan Mountains to the north (Fig. 1). These mountains have an average elevation of 1000–2000 m and lie next to the north China plains with a sharp slope at the east and south sides, respectively. Chen and Lu (2015) indicated that the EH-related circulation anomalies for WNC, because of its special location on the leeside regions, present distinct large-scale and local features: on the one hand, there is a large-scale anomalous cyclone to the northeast of WNC, and northwesterlies prevail over WNC, which is different from the typical anticyclonic anomalies characterizing most of the other parts of eastern China; on the other hand, the lower-tropospheric northwesterlies blow nearly normal to the mountain ranges and bring warmer and drier air from the mountains to the north China plain areas, favoring the foehn effect and efficiently increasing the surface air temperature on the lee side.

Some studies have exhibited that the foehn is a significant phenomenon in WNC. For instance, Wang et al. (2012a) used the hourly observational data from the automatic meteorological observation stations over the eastern lee side of the Taihang Mountains during 2007–08 to define 19 foehn cases in western north China and indicated that the westerly foehn results in dramatic warming over the lee side. However, they only used the surface observational data for analysis and did not analyze the large-scale circulation. On the other hand, model simulations have also been employed to explore the mechanism of foehn occurrence over western north China. Wang et al. (2012b) used the WRF Model to simulate a typical foehn case over the eastern lee side of the Taihang Mountains and suggested that the formation and movement of the foehn is closely related to the lee wave associated with the northwesterly or westerly flow going over the mountains. However, compared with the observation, the model has an obvious deficiency of simulating an earlier formation and faster propagation of the foehn. In fact, the topographies over western north China are quite complicated (Fig. 1b), covering mountains, basins, and plateaus, and make the mesoscale simulation over this area very challenged. Furthermore, the lack of high-resolution observational data over western north China makes the evaluation of model behaviors quite difficult. Therefore, we constrain the present study to statistical analyses based on reanalysis and observational data and leave model simulations to the future.
Besides the terrain effect, WNC is also influenced by the East Asian summer monsoonal circulation. In the lower troposphere, monsoonal southwesterlies prevail in eastern China and curve eastward in north China (Fig. 1a). The weakening (strengthening) of the southwesterly brings less (more) water vapor to north China, favoring higher (lower) temperature. The merging of the monsoonal flow and foehn flow makes specific studies on WNC scientifically important, especially the interaction between large-scale and local circulations. Moreover, the WNC covers many metropolises in north China, such as Beijing (the capital of China), Shijiazhuang (the capital city of Hebei province), and Zhengzhou (the capital city of Henan province). The dense population and economic concentration in these regions require better understanding of the mechanisms that affect the EH in WNC. For instance, the population in Beijing has exceeded 20 million and is growing at a speed of 0.5 million per year.

The foehn wind is an important local circulation in the regions situated on the lee of large mountain ranges all over the world, where they can be responsible for warming of more than 28°C (Math 1934; McGowan and Sturman 1996; Speirs et al. 2010). In WNC, the northwesterly foehn is observed to have a horizontal scale of around 100 km and bring rapid temperature enhancement of 13.5°C within 30 min (Zhao et al. 1993; Wang et al. 2012a). On the other hand, the local foehn is usually related to large-scale circulation. For example, Shibata et al. (2010) investigated the role of large-scale circulation in triggering the foehn in the northern lee-side plain areas over central Japan and suggested that the occurrence of the southerly foehn is associated with the intensification of the North Pacific high, which enhances the northwest–southeast pressure gradient. Steinhoff et al. (2014) indicated that a large range of synoptic-scale circulation patterns can drive the foehn events over the McMurdo Dry Valleys of Antarctica, and the warmest foehn events are typically associated with blocking highs over the Southern Ocean. Investigating the mechanisms of how the large-scale circulation potentially favors the occurrence of the local foehn phenomenon during EH days in WNC is one of the main motivations of this study.

Apart from the northwesterly foehn effect, some previous studies indicated that the EH over WNC can also result from a large-scale anticyclone. For instance, Qian et al. (2005) analyzed an EH events in 2000 over Beijing, which is included in WNC, and indicated that the increased temperature is related to a strong anticyclone stretching from the lower to upper troposphere. Zheng and Wang (2006) performed composite analyses for the 11 EH events over Beijing during 1996 to 2000 and also obtained similar results. In contrast, Chen and Lu (2014a,b) conducted composite analyses for the EH in Beijing during 1979 to 2008, and showed that the circulation is characterized by a significant cyclonic anomaly occurring in both the lower and upper troposphere. This inconsistency implies that the circulation patterns responsible for the EH in WNC can be various, either anomalous anticyclone or cyclone. Recently, Takane et al. (2014) categorized the circulation patterns associated with the EH in the inland part of the Tokyo metropolitan area, which is located on the eastern lee side of mountain ranges lying along the southwest–northeast orientation. They showed that the synoptic surface pressure patterns responsible for EH mainly appear to be three different categories: the trough around central Japan (accounting for 41.3%), the high pressure in the south and low pressure in the north (24.0%), and the high pressure in the east and low pressure in the west (9.3%). Categorizing the circulation patterns associated with the EH in WNC is another main motivation of the present study.

The remainder of the paper is organized as follows: Data and definitions are described in section 2. In section 3, we compare the anomalies associated with the foehn-favorable and no-foehn EH in WNC and find that they are related to cyclonic and anticyclonic anomalies, respectively. Therefore, in section 4 the influences of anomalous cyclonic and anticyclonic circulations on air temperature are compared, before we present the conclusions of the study in section 5.

2. Data and definition

a. Data

The data used in the study span the 30 summers (June–August) from 1979 to 2008. The homogenized daily mean/maximum/minimum surface air temperature series of 549 National Standard Stations in China (accessed 15 January 2013; Li and Yan 2009, 2010) are used. The homogenization of temperature data efficiently revises the inhomogeneity in temperature data caused by frequent changes of observing locations and protocols (Li and Yan 2010). For example, the annual inhomogeneity for Beijing temperature ranges between −0.21°C and 0.48°C.

The 6-hourly data from the European Center for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim, accessed 15 January 2013; Dee et al. 2011) are used to analyze the associated circulation anomalies. The data at 0600 UTC (i.e., 1400 local standard time (LST)) are used to analyze the EH-related anomalies. The horizontal resolution is 1.5° × 1.5°, and the 23 pressure levels from 1000 to 200 hPa are
used for analysis. The ERA-Interim data are unsuited to discuss details of the foehn. Therefore, we focus on large-scale and synoptic-scale conditions, not mesoscale details. Topography data ETOPO1 with a cell size of 1 arc-minute are from the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA) (Amante and Eakins 2009).

b. Definitions

The domain of western north China is the same as the definition of Chen and Lu (2015). The WNC region includes 24 stations over which the EH-related circulation pattern exhibits poor spatial correlation with the averaged pattern of eastern China. This indicates that WNC is unique in terms of the EH-related circulation, with most of the stations located on the eastern lee side of the Taihang Mountains (Fig. 1b).

EH is defined as days upon which more than half of the 24 stations in WNC present daily maximum surface air temperature \( T_{\text{max}} \) exceeding 35°C. The threshold of 35°C is employed by the China Meteorological Administration to define EH and has been widely used by previous studies (e.g., Wei and Sun 2007; Wei and Chen 2009; Chen and Lu 2014a,b). Based on this definition, there are a total of 173 EH days in WNC, accounting for 6% of all summer days (2760 days).

Composite analyses are performed to investigate the synoptic anomalies. Anomalies are computed by subtracting the climatological mean (from 1979 to 2008) of the identical days from the raw data. These anomalies are compared to the whole summertime series for significance estimation, using the Student’s \( t \) test and significance level of 95%. Effective sample lengths are used because of the persistence in the analysis series (Wilks 2006).

3. Comparisons of the anomalies associated with the foehn-favorable and no-foehn EH

In this section, in order to obtain the synoptic disturbances inducing EH days, the composite anomalies are averaged from −2 to 0 days of the EH unless mentioned otherwise. This averaging period is identical to that of Chen and Lu (2015). Figure 1a shows the composite anomaly of \( T_{\text{max}} \) for the EH in WNC. The surface air temperature greatly increases over WNC on EH days, with maximum amplitude of +3°C right over the stations.

Figure 2 exhibits the composite anomalies of winds for the EH days in WNC. There is a significant anticyclonic anomaly to the northwest of WNC in the upper and middle troposphere, and northerly flows occur over WNC (Figs. 2a,b). In the lower troposphere, the anticyclone becomes quite weak, and instead a significant cyclonic

![Composite anomalies averaged from −2 to 0 days for the EH in WNC: (a) 200-hPa, (b) 500-hPa, and (c) 850-hPa winds (m s\(^{-1}\)) and (d) winds along the section from (45°N, 105°E) to (30°N, 120°E) (units of the reference vector are 1.0 m s\(^{-1}\) for the horizontal velocity and 1.0 \( \times 10^{-2} \) hPa s\(^{-1}\) for the vertical velocity).](image-url)
anomaly occurs to the northeast of WNC, and the associated northwesterlies prevail over WNC (Fig. 2c). Combining the topography shown in Fig. 1, it is clear that the lower-tropospheric northwesterlies blow from the mountain to the plain areas, nearly orthogonal to the contours of elevation. Figure 2d demonstrates the wind anomalies in the vertical section across the mountain–plain area from (45°N, 105°E) to (30°N, 120°E), denoted by the red dashed line in Fig. 2c. There are obvious winds blowing from the mountains to the plains and then sinks on the lee side, forming strong descending motion in the lower troposphere (Fig. 2d). These results indicate that the northwesterlies over mountains provide a favorable environment for the occurrence of the foehn effect on EH days in WNC, consistent with previous studies (Wang et al. 2012a; Chen and Lu 2015). In addition, there is strong subsidence above the 850-hPa level over both the mountain and plain areas, indicating the importance of large-scale circulation.

To better investigate the role of large-scale circulation in local foehn and their impact on the occurrence of EH in WNC, the EH days are categorized into foehn-favorable and no-foehn types. First, we defined a foehn index V850, which is the anomalous 850-hPa northwesterly wind speed averaged from (42°N, 108°E) to (38°N, 112°E) along the section shown in Fig. 2c. In climatology, the 850-hPa wind averaged from (42°N, 108°E) to (38°N, 112°E) shows a northwesterly component with amplitude of about 1.0 m s⁻¹. Thus, the actual 850-hPa horizontal winds blow from the mountains to the plains on the days with positive V850, indicating a favorable large-scale environment for the occurrence of foehn, while the days with negative V850 inhibit the formation of foehn. Accordingly, the EH days with positive (negative) V850 are classified as foehn-favorable (no-foehn) EH days, and there are 122 foehn-favorable EH days and 51 no-foehn EH days. The foehn-favorable circulation appears in 70% of the EH days, playing an important role in the occurrence of EH in WNC.

Figure 3 demonstrates the evolution of composite $T_{max}$ anomaly from −5 to +5 days for the foehn-favorable and no-foehn EH, respectively. Both types of EH show positive anomalies during the whole period. The positive anomalies rapidly increase from −2 to 0 days and decrease from 0 to +2 days and get the maximum values on 0 day. This indicates that the occurrences of both types of EH are basically related to synoptic disturbances, and it is reasonable to average from −2 to 0 days so as to analyze the synoptic disturbances responsible for temperature increase.

Figure 4 exhibits the composite anomalies for the foehn-favorable EH days. There is an anomalous anticyclone to the northwest of WNC and a cyclone to the northeast in the whole troposphere, presenting a barotropic structure (Figs. 4a–c). The anticyclone gets weaker while the cyclone gets stronger from the upper to lower troposphere. The upper- and midtropospheric cyclonic anomalies are distinct from the anomalies for all EH (Figs. 2a, b). Associated with the anticyclone and cyclone, there are anomalous northerlies over WNC in the upper troposphere and northwesterlies in the middle and lower troposphere. We also checked the actual lower-tropospheric winds averaged on foehn-favorable EH days (not shown) and found that there is an obvious northwesterly along the northwest half of the section trace (i.e., at the upstream of WNC), confirming the actual existence of foehn-favorable circulation. The vertical section across the mountain–plain area shows wind anomalies similar to those for all EH days, but with much larger amplitudes (Figs. 4d, 2d). There are strong northwesterlies blowing from the mountains to the plains, and significant subsidence occurs on the lee side, potentially favorable for the foehn effect. Furthermore, there is also anomalous large-scale subsidence above the 850-hPa level over both the mountain and plain areas.

The 500-hPa vertical velocity exhibits a significant descending anomaly over WNC (Fig. 4e), which is consistent with the northwesterlies in the southwestern quadrant of the cyclone (Fig. 4b). Therefore, the northwesterlies associated with the barotropic cyclone are important for the occurrence of both foehn and large-scale subsidence. Moreover, the anomalous descending and northwesterlies together lead to lower humidity, and the 850-hPa relative humidity significantly decreases over WNC (Fig. 4f), as does the specific humidity (not shown). The anomalous descending would increase the air temperature through adiabatic heating, and the lower humidity would increase the air
Fig. 4. Composite anomalies averaged from −2 to 0 days for the foehn-favorable EH in WNC: (a) 200-hPa, (b) 500-hPa, and (c) 850-hPa winds (m s$^{-1}$); (d) winds along the section from (45°N, 105°E) to (30°N, 120°E) (units of the reference vector are 1.0 m s$^{-1}$ for the horizontal velocity and 1.0 × 10$^{-4}$ hPa s$^{-1}$ for the vertical velocity), (e) 500-hPa vertical velocity ($\text{d}p/\text{d}t$) (10$^{-4}$ hPa s$^{-1}$; contour interval: 2 × 10$^{-4}$ hPa s$^{-1}$), (f) 850-hPa relative humidity (%; contour interval: 3%), and (g) $T_{\text{max}}$ (the numbers denote the amplitudes of temperature anomalies over the corresponding stations; K). The yellow shaded areas are statistically significant at the 95% confidence level according to the Student’s $t$ test. The rectangle in Fig. 4b denotes the domain used later to define the anticyclone index.
temperature through reducing the scattering and absorption of solar radiation by water vapor. As a result, the surface air temperature evidently increases over WNC, and the higher temperature extends to the surrounding areas (Fig. 4g), which is consistent with the large-scale descent aloft. Also evident is that the stations with highest temperature anomalies (marked by red dots and purple dots) are well located close to the eastern mountain slope, which are obviously higher than the plain areas farther away from the mountains and indicate the influence of the local foehn effect.

The composite anomalies for the no-foehn EH are quite different from the foehn-favorable EH (Fig. 5). In the upper and middle troposphere, a significant anticyclonic anomaly appears north of WNC (Figs. 5a,b), which is obviously stronger and extends farther eastward in comparison with the one for all EH days (Figs. 2a,b). Associated with the upper-tropospheric anticyclone and cyclone south to it, anomalous easterlies prevail over WNC. In climatology, the East Asian upper-tropospheric westerly jet (EAJ) appears around 40°N, and WNC is located south of the jet axis. Thus, the strong easterly anomaly indicates an obviously decreased EAJ. To assess the strength of EAJ, the EAJ index (EAJI) appears around 40°N, which is obviously lower than those around the leeside areas in the lower troposphere. The air temperature significantly increases in the upper troposphere for both types of EH and decreases in the upper levels (Fig. 6c). The decrease of temperature from the lower to middle troposphere is faster for the foehn-favorable EH than for the no-foehn EH, and it is due to the stronger cold advection (Fig. 6d) associated with the northerly winds for the foehn-favorable EH (Figs. 4a,b). The negative midtropospheric temperature anomaly for the foehn-favorable EH indicates that the adiabatic heating associated with large-scale subsidence is offset by cold advection. In contrast, the obvious warming confined in the lower troposphere is favored by the stronger subsidence over leeside and lower-tropospheric warm advection (Fig. 6d). The stronger lower-tropospheric warm advection for foehn-favorable EH mainly results from the local rather than large-scale temperature advection, because the ambient temperature anomalies are obviously lower than those around the leeside areas in the lower troposphere (not shown), similar to the surface air temperature anomalies as shown in Fig. 4g.

Figure 6 shows the vertical profiles of anomalies averaged over the WNC stations for the foehn-favorable and no-foehn EH. There is obvious subsidence in the whole troposphere for the foehn-favorable EH (Fig. 6a). The subsidence gets largest in the middle troposphere and increases again below the 850-hPa level, with the former one related to large-scale subsidence and the latter one related to foehn-favorable circulation. For the no-foehn EH, the strongest subsidence occurs near the 300-hPa level, then decreases in the lower levels. Thus, the upper-tropospheric subsidence is important for the higher temperature on no-foehn EH days. The relative humidity obviously decreases in the whole troposphere for the foehn-favorable EH, and the largest amplitude occurs below 850 hPa (Fig. 6b), which is related to the potential foehn effect. In contrast, the relative humidity anomaly for no-foehn EH is obviously weaker, and the largest amplitude occurs in the middle troposphere. The air temperature significantly increases in the lower troposphere for both types of EH and decreases in the upper levels (Fig. 6c). The decrease of temperature from the lower to middle troposphere is faster for the foehn-favorable EH than for the no-foehn EH, and it is due to the stronger cold advection (Fig. 6d) associated with the northerly winds for the foehn-favorable EH (Figs. 4a,b). The negative midtropospheric temperature anomaly for the foehn-favorable EH indicates that the adiabatic heating associated with large-scale subsidence is offset by cold advection. In contrast, the obvious warming confined in the lower troposphere is favored by the stronger subsidence over leeside and lower-tropospheric warm advection (Fig. 6d). The stronger lower-tropospheric warm advection for foehn-favorable EH mainly results from the local rather than large-scale temperature advection, because the ambient temperature anomalies are obviously lower than those around the leeside areas in the lower troposphere (not shown), similar to the surface air temperature anomalies as shown in Fig. 4g.

The above results suggest a clear distinction between the foehn-favorable and no-foehn EH, with the former one involving an anomalous cyclone, while the latter one involves an anomalous anticyclone. To compare the roles of foehn and anticyclone in the occurrence of EH, an anticyclone index H500 is defined as the 500-hPa geopotential height anomaly averaged over (35°–50°N, 110°–130°E) (denoted

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Fig. 5. As in Fig. 4, but for the no-foehn EH in WNC.
by the red rectangles in Figs. 4b, 5b). This domain is located at the 500-hPa anomalous cyclone (anticyclone) for foehn-favorable (no-foehn) EH days, and positive (negative) H500 denotes an anticyclonic (cyclonic) anomaly. Figure 7 shows the scatterplot of the foehn index (V850) and anticyclone index (H500) for all EH days. It is clear that the two indices are negatively correlated, with a correlation coefficient as high as -0.75. This suggests that the foehn-favorable circulation is closely related to a 500-hPa cyclonic anomaly, consistent with Fig. 4b. More than half (55%) of the EH days are in the fourth quadrant with positive V850 and negative H500, mainly influenced by the foehn-favorable circulation; 22% of the EH days are in the second quadrant with positive H500 and negative V850, mainly influenced by the anticyclone; 15% of the cases are in the first quadrant with positive V850 and positive H500, jointly influenced by the foehn-favorable circulation and anticyclone, but no case in this quadrant shows a combination of both large V850 and large H500. The cases in the third quadrant with negative V850 and negative H500, which is influenced by neither the foehn nor the anticyclone, only account for a very small proportion of 8%. Therefore, the occurrence of EH days in WNC is mostly caused by either the foehn-favorable circulation or the anomalous anticyclone, and the former one plays a more important role.

4. Comparisons of the influence of cyclonic and anticyclonic circulation patterns on air temperature

The previous section shows that both cyclonic anomaly (foehn-favorable EH) and anticyclonic anomaly (no-foehn EH) can lead to higher temperature over WNC, which is different from the typical configuration of a cyclonic (anticyclonic) anomaly causing lower (higher) temperature. In this section, we explore the impact of these two circulation patterns on temperature anomalies in a more general sense, examining the ordinary days...
without EH (no EH) and comparing the higher and lower temperature composites.

Figure 8a demonstrates the scatterplot of the anomalous 2-m air temperature averaged over the WNC stations (t2m) versus the anticyclone index (H500) on the identical days. Consistent with the previous section, most of the foehn-favorable EH (red dots) exhibits a cyclonic anomaly (79%), while most of the no-foehn EH (blue dots) exhibits an anticyclonic anomaly (69%). Excluding the 173 EH days, there are 2587 no-EH days (gray dots) in the summertime series (JJA in 1979–2008), with 24.4% (633 days) in the first quadrant (defined as positive t2m and positive H500), 27.0% (698 days) in the second quadrant (defined as negative t2m and positive H500), 21.4% (553 days) in the third quadrant (defined as negative t2m and negative H500), and 27.2% (703 days) in the fourth quadrant (defined as positive t2m and negative H500). The proportions in each quadrant are roughly the same, indicating the equally important roles of anticyclonic and cyclonic anomalies in causing higher or lower temperature. The composite circulation anomalies for the four quadrants will be compared in the rest of this section. It should be mentioned that all the presented results for the no-EH days are quite similar to those for all summer days (not shown), since the no-EH days account for the majority (94%) of all summer days.

Scatterplot of t2m versus V850 on the identical days shows similar features (Fig. 8b). Noticing the foehn-favorable and no-foehn EH are classified by the northwesterly anomalies averaged from $-2$ to 0 days in the previous section, while the scatterplot is based on the anomalies on 0 day, it is understandable that there is a small portion of foehn-favorable EH (18%) with negative V850 and no-foehn EH (25%) with positive V850 on 0 day, because of the strong day-to-day variation of local winds. There are similar proportions in each quadrant for the no-EH days (gray dots), which indicates that both northwesterly (positive V850) and southeasterly (negative V850) are important in causing higher or lower temperature, confirming the complexity of circulation–temperature configurations over WNC.

Figure 9 shows the composite wind anomalies for the no-EH days in the four quadrants of the t2m versus...
H500 scatterplot, respectively. We first focused on the first and fourth quadrants of higher temperature composites. For the first quadrant, there is an anomalous anticyclone to the north and a cyclone to the south of WNC in the upper troposphere, and strong easterly anomalies prevail over WNC, indicating the decrease of EAJ (Fig. 9a). The EAJI is 18.4 m s$^{-1}$ for the first quadrant, reduced by 6.5 m s$^{-1}$ compared to climatology. In the middle and lower troposphere, the anticyclone is located to the northeast of WNC, and easterlies or southerlies occur over WNC (Figs. 9b,c). The vertical section across the mountain–plain area shows anomalous subsidence over the plains and ascendancy over the mountains (Fig. 9d), and the former one is favorable for higher temperature via adiabatic heating.

These circulation anomalies resemble well those for no-foehn EH (Figs. 5a–d), suggesting that both the no-foehn EH and higher temperature for the first quadrant result from the midlatitude anticyclonic anomalies. Therefore, an identical or similar mechanism would be responsible for causing both the no-foehn EH and higher temperature. However, it should be mentioned that there are some notable differences in the upper-tropospheric circulation anomalies between the general higher temperature (or, more exactly, the first quadrant; Fig. 9a) and no-foehn EH (Fig. 5a). First, the anticyclone in Fig. 9a is slightly shifted eastward, and this eastward displacement is not because of the general eastward propagation of synoptic disturbances in the middle latitudes, because the discrepancy still exists even if we repeat the composite analysis only on the no-foehn EH days (i.e., 0 day), rather than during the earlier period from $-2$ to 0 days (results not shown). Second, the cyclone south to WNC presents a zonal orientation for the first quadrant, but it extends northeastward into northeast Asia for the no-foehn EH. Despite these differences, we can conclude that the similarities are predominant between the first quadrant and no-foehn EH, particularly in the middle and lower troposphere.

For the fourth quadrant, with negative height anomalies causing higher temperature, there is an obvious cyclone to the northeast of WNC in the whole troposphere, presenting a barotropic structure, and northwesterlies prevail over WNC (Figs. 9m–o). The anomaly of EAJ for the fourth quadrant is much less obvious than for the first quadrant: the EAJI for the fourth quadrant (28.2 m s$^{-1}$) is only 3.3 m s$^{-1}$ higher than the climatological one (24.9 m s$^{-1}$). The vertical section across the mountain–plain area demonstrates significant subsidence above both the plain and mountain areas (Fig. 9p). Meanwhile, obvious northwesterlies occur near the mountain surface, blow toward the plains and subside over the lee side, potentially favoring the occurrence of foehn. These anomalies for the fourth quadrant are similar to those for the foehn-favorable EH (Figs. 4a–d), indicating the same mechanism is responsible for the higher temperature in this quadrant as the foehn-favorable EH. Again, if the composite analysis is repeated by using only the foehn-favorable EH days (i.e., 0 day) in the upper troposphere, the cyclonic anomaly is intensified and the anticyclonic anomaly west to it becomes much weaker but without change in their locations (not shown), in comparison with the anomalies for the earlier period from $-2$ to 0 days shown in Fig. 4a.
which may be due to the eastward dispersion of Rossby waves. The anomalies for the second (third) quadrant (Figs. 9e–l) are almost opposite to the above-mentioned anomalies for the fourth (first) quadrant. The lower temperature is related to the stronger ascent over the lee side in the second quadrant and associated with the anomalous cyclonic circulation in the third quadrant.

Figure 10 shows the composite anomalies of 500-hPa vertical velocity, 850-hPa relative humidity, and $T_{\text{max}}$ for the no-EH days in the four quadrants. For the first quadrant, the 500-hPa vertical velocity and 850-hPa relative humidity anomalies are quite weak (Figs. 10a,b). Associated with the anticyclonic anomaly, surface air temperature significantly increases over WNC (Fig. 10c) and extends over northeast Asia, corresponding to the lower-tropospheric anticyclonic domain (using re-analysis data of 2-m air temperature; not shown), which is similar to no-foehn EH but with much smaller amplitudes. Composites for the fourth quadrant are similar to the foehn-favorable EH: associated with the northwesterlies, there is anomalous subsidence, lower relative humidity, and higher temperature over WNC (Figs. 10j–l). The higher temperature related with foehn-favorable circulation is quite localized over WNC (Fig. 10l), and large-scale lower temperature still occurs over the northeastern regions of the lower-tropospheric cyclonic
domain (using reanalysis of 2-m air temperature; not shown).

The composites for the second (third) quadrant (Figs. 10d–i) are almost opposite to the fourth (first) quadrant. Taken together, the temperature anomalies for the first and second quadrants are both characterized by large-scale higher temperature associated with the anticyclonic anomaly. However, the second-quadrant cases are also influenced by stronger ascent over the lee side, favoring higher relative humidity, adiabatic cooling, and consequent local lower temperature over WNC. Similarly, the fourth quadrant shows localized higher temperature over WNC resulting from stronger terrain-induced descent, distinct from the large-scale lower temperature that corresponds well to the cyclonic anomaly over northeast Asia for the third quadrant. Therefore, the first and third quadrants illustrate the influence of large-scale circulation on air temperature, while the second and fourth quadrants additionally highlight the effect of large-scale circulation on local topographic circulation and their impacts on surface air temperature.

Figure 11 shows the vertical profiles of anomalies averaged over the WNC stations for the no-EH days in the four quadrants. The anomalies for the first (fourth) quadrants are opposite to the third (second) quadrants, so we focus on the comparison between the first and fourth quadrants (the blue and red solid lines). The profiles of all the variables for the first (fourth) quadrant are similar to those for the no-foehn (foehn favorable) EH (Fig. 6), albeit with smaller anomaly amplitudes, confirming that the two types of EH are representative of different configurations between circulation and temperature anomalies, and the stronger circulation anomalies favor the higher temperature on EH days. For example, comparing Fig. 6a and Fig. 11a, the vertical profiles of vertical velocity for no-foehn (foehn favorable) EH show larger amplitudes than the first (fourth) quadrant: the largest vertical velocity anomaly is $3.2 \times 10^{-4}$ hPa s$^{-1}$ ($6.0 \times 10^{-4}$ hPa s$^{-1}$) for no-foehn (foehn favorable) EH, and only $1.2 \times 10^{-4}$ hPa s$^{-1}$ ($4.5 \times 10^{-4}$ hPa s$^{-1}$) for the first (fourth) quadrant. The stronger anomalous subsidence is favorable for stronger adiabatic warming and resultant higher temperature on EH days.
The aforementioned differences between different quadrants can be explained by the diverse patterns of anticyclones/cyclones. Taking the first and second quadrants, for example, the first quadrant presents an anticyclone accompanied by a cyclone in the south and easterlies over WNC in the upper troposphere (Fig. 9a), while the second quadrant presents an upper-tropospheric anticyclone with southeasterlies over WNC (Fig. 9e). For the first quadrant, associated with the anticyclone shifting southeastwards from the upper to lower troposphere, the lower-tropospheric wind anomalies present a negative vorticity southeast of WNC, which would form an anomalous divergence with the influence of surface friction, and together with the upper-tropospheric cyclone lead to anomalous subsidence to the southeast of WNC (Fig. 9d). Meanwhile, the anomalous lower- and midtropospheric southerlies to the northwest of WNC would favor ascendant anomaly. In contrast, for the second quadrant, southeasterly anomalies prevail over WNC in the whole troposphere (Figs. 9e–g). The southeasterlies induce anomalous warm advection in the middle and upper troposphere (Fig. 11d) and thus force large-scale anomalous ascendant air parcels over WNC (Fig. 9h). In addition, the lower-tropospheric southeasterlies induce stronger ascendant over the lee side through interaction with the terrain. The stronger ascendant for the second quadrant would increase adiabatic cooling and humidity and results in lower surface air temperature over WNC (Fig. 10f), distinct from the large-scale higher temperature associated with the anticyclone for the first quadrant (Fig. 10c). The differences between the third and fourth quadrants are roughly converse to the above-described features, which is expectable because of the antisymmetric anomalies between the second (third) quadrant and the fourth (first) quadrant.

**Fig. 11.** Vertical profiles of the anomalies averaged over the stations in WNC for the no-EH days in the four quadrants: (a) vertical velocity \( \frac{dp}{dt} \) \(10^{-4}\text{hPa s}^{-1}\); (b) relative humidity (%); (c) temperature (K); and (d) horizontal temperature advection \(10^{-5}\text{K s}^{-1}\). Lines denote the following quadrants: first quadrant (solid blue), second quadrant (dashed red), third quadrant (dashed blue), and fourth quadrant (solid red).
The results in this section indicate that the surface air temperatures are determined by the total effects of two offsetting factors: large-scale anticyclonic (cyclonic) anomalies and terrain-induced ascent (descent) anomalies favored by the large-scale circulation. When anticyclonic or terrain-induced descent anomalies are dominant in comparison with terrain-induced ascent or cyclonic anomalies, higher temperatures occur over WNC; lower temperatures occur otherwise. The results for the higher temperatures are dynamically consistent with those particularly for EH shown in the previous section, suggesting the same mechanism is responsible for the extreme and moderate heats.

It should be mentioned that the present study focused on the composite anomalies in order to better illustrate the circulation related to EH. However, foehn or the foehn-favorable circulation is a result of actual leeside descent. Therefore, we repeated the relevant analysis by using the actual winds, rather than the anomalies, and showed the actual winds along the vertical section averaged on foehn-favorable EH days in Fig. 12. It is shown that over the leeside region, obvious descent occurs only below 850 hPa, while ascent occurs in the upper layers between 600 and 850 hPa. The localized leeside descent in the lower layers is associated with the northwesterlies blowing over the mountain surface and is clearly independent of the large-scale descent over plains. Therefore, both actual foehn effect and large-scale descent occur on foehn-favorable EH and contribute to the higher surface air temperature, underpinning the above analysis.

5. Conclusions

Western north China (WNC), located on the southeastern lee side of the Taihang Mountains and Yan Mountains, is potentially influenced by the foehn effect on extreme heat (EH) days. The present study classified the EH days into foehn-favorable EH and no-foehn EH according to whether there are anomalous northwesterlies over mountains or not and performed composite analyses to investigate the role of large-scale circulation in inducing local foehn flow and their impacts on the EH occurrence, using homogenized daily surface air temperature data for China and 6-hourly ERA-Interim data for the summers from 1979 to 2008.

The foehn-favorable EH is characterized by a barotropic cyclonic anomaly located to the northeast of WNC, and anomalous northwesterlies associated with the cyclone prevail over WNC. The anomalous northwesterlies are critical for the occurrence of foehn-favorable EH. The northwesterlies not only lead to anomalous large-scale subsidence but also bring the warmer and drier air from the mountains to the plains in the lower troposphere and sinks on the leeside regions, providing a favorable environment for the occurrence of the foehn effect. The foehn-related and large-scale descents also occur in the actual winds, rather than the anomalies, and they appear to be distinguished from one another, suggesting the actual existence of foehn flows. The strong descents result in local higher temperature over WNC, and the highest temperature anomalies are well located close to the eastern mountain slope, manifesting the influence of the foehn effect. In comparison, the no-foehn EH is characterized by significantly different large-scale circulation anomalies. There is an anomalous anticyclone to the north and a cyclone to the south of WNC in the upper troposphere. The anomalous anticyclone becomes much weaker in the lower troposphere, and no significant wind occurs over WNC. Associated with the anticyclone, higher temperature occurs over a broad area, including WNC and the region north of it.

It is interesting that both cyclonic and anticyclonic anomalies can induce EH over WNC. To further investigate the relationship between circulation and temperature, and to distinguish the cyclonic and anticyclonic anomalies causing higher temperatures from those causing lower temperatures, we perform composite analyses on all the summer days but removing EH days, according to the configuration of temperature anomalies and 500-hPa height anomalies. The results indicate that large-scale
anticyclonic and cyclonic anomalies would interact with topography and favor the occurrence of local terrain-induced ascent and descent anomalies, respectively. Therefore, the surface air temperatures over WNC are determined by both large-scale and local circulations, which play offsetting roles in affecting temperatures. Higher temperatures occur over WNC if the heating caused by anticyclonic anomalies is greater than the cooling caused by terrain-induced ascent or if the cooling by cyclonic anomalies is weaker than the heating by terrain-induced descent. Otherwise, lower temperatures occur over WNC. The temperature anomalies associated with terrain-induced flows are confined over WNC, while the anomalies determined by large-scale circulation occur over northeast Asia, well corresponding to the anticyclonic or cyclonic domain. It is found that whether there are the cyclonic or anticyclonic anomalies in the upper troposphere south of WNC can be used as an indicator to distinguish the circulation patterns causing higher or lower temperatures. This difference in the upper troposphere is associated with whether there are anomalous northwesterlies or southeasterlies in the lower troposphere over WNC, which cause anomalous descent or ascent over the lee side. Furthermore, the results for higher temperatures are consistent with those for EH, confirming the proposed mechanism for EH occurrence. Therefore, when analyzing the circulations responsible for the temperature variability over WNC, not only the large-scale circulation but also its effect on local topographic flows should be considered, and it is encouraging to see that the large-scale settings associated with local topographic flows are distinguished.

The present results have some implications. First, this study indicates that the EH over WNC can be categorized into foehn-favorable EH and no-foehn EH, and these two kinds of EH are caused by distinct circulations. Therefore, these two kinds of EH should be separately investigated if one attempts to better understand the mechanism responsible for EH occurrence over WNC. It can be hypothesized that, in particular, the foehn-favorable EH and no-foehn EH would have distinct precursory large-scale circulation patterns, and thus these patterns should be examined respectively. Understanding of the precursory patterns will be useful for improving the weather forecasts. Second, it would be interesting to investigate the accuracy of temperature forecast for the foehn-favorable EH and no-foehn EH, respectively in the current numerical weather forecasting systems. This kind of comparison between the foehn-favorable and no-foehn EH may provide some hints to improve the accuracy of temperature forecast. Third, this study may provide a basis for a better understanding of circulations responsible for temperature variability at many locations with remarkable topographic relief all over the world. The EH over these places may not be attributed to anticyclonic circulation alone. In fact, EH tends to be weakly associated with anticyclonic anomalies over the regions east to the Rocky Mountains (Loikith and Broccoli 2012, their Fig. 4), where the westerly foehn circulation usually induces higher temperatures (Oard 1993; Mercer et al. 2008). Furthermore, it is expected that EH will generally occur more frequently under global warming. However, regional trends are also closely dependent on the changes of regional circulation patterns (Horton et al. 2015). Therefore, it would be expected that the challenge of evaluating and projecting reliably the change in EH under global warming is more enormous for the regions such as WNC, where the regional circulation patterns related to EH are complicated.

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