Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018

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Abstract

Two intense heatwaves of July and early August 2018 are found to be associated with a European blocking (EB) event accompanied by a series of consecutive positive North Atlantic Oscillation (NAO+) events. Further analyses show that the collaborative role of an EB event and its upstream NAO+ pattern could increase the frequency, persistence, magnitude and scale of heatwaves over Europe. Compared with NAO+-unrelated EB events, NAO+-related EB events are less movable (quasi-stationary) and more persistent over Europe, which could contribute to an increase in the intensity and persistence of heatwaves. In addition, the blocking high of this type has a northeast–southwest orientation with stronger warm airflow and less precipitation in northern and western Europe, where large scopes of higher temperatures tend to occur. In contrast, NAO+-unrelated EB events without orientation correspond to a trough in the south, which results in increased precipitation and cold air in the southern part of Europe, and thus high temperatures contract to the northern part of Europe. Moreover, considering that the NAO+ pattern leads the formation of an EB event, the NAO+ pattern might serve as a potential predictor for European heatwaves. Our conclusions are strongly supported by the analysis of CMIP6 historical simulations which also capture the differences of high temperatures and atmospheric circulations between NAO+-related EB events and NAO+-unrelated EB events.

1. Introduction

Heatwaves can bring about disastrous socio-economic impacts (Mechler et al 2010, Forzieri et al 2018, Schaller et al 2018). As the global-mean surface air temperature has increased rapidly (Sippel et al 2020), we have witnessed a series of heatwaves across Europe (e.g. 2003 in central and southern Europe, 2010 in eastern Europe and Russia, 2015 in central Europe, and 2017 in western Europe) (Fischer et al 2007, Russo et al 2015, Rasmijn et al 2018, Sanchez-Benitez et al 2018). In particular, the heatwave in summer 2003 was the warmest since 1500, resulting in 70 000 deaths in 12 European countries (Stefanon et al 2012). During the exceptional heatwave of summer 2010, many cities in eastern Europe experienced record extreme hot weather, which led to about 55 000 deaths and economic losses of $15 billion USD in Russia (Barriopedro et al 2011, Simmonds 2018).

The occurrence of more severe, more frequent and longer-lived heatwaves in Europe (Meehl and Tebaldi 2004), together with their serious consequences, has triggered many mechanistic analyses, especially from the atmospheric perspective (Schneider et al 2012, Coumou et al 2014, Horton et al 2015, Mann et al 2018, Schaller et al 2018, Sousa et al 2018). Heatwaves are typically controlled by atmospheric anticyclones, either embedded in the wave train or as atmospheric blockings (Chen and Newman 1998, Fischer et al 2007, Li et al 2019, 2020b), which can cause high temperatures by
increasing clear-sky solar radiation, air subsidence and warm advection (Horton et al. 2016). Extreme weather events at mid-latitudes are closely related to the presence of quasi-stationary and amplified planetary waves (Francis and Vavrus 2012, Petoukhov et al. 2013, Coundou et al. 2014, 2018, Screen and Simmonds 2014, Yao et al. 2017, Kornhuber et al. 2019). Petoukhov et al. (2013) found that it might be possible to explain these extreme weather events by the quasi-resonant amplification of wave trains with zonal wavenumbers 6–8. Coundou et al. (2014) further applied this quasi-resonant theory to extreme heat and extreme rainfall in boreal summer. Additionally, Kornhuber et al. (2019) noted that the heatwave of early summer 2018 matched well with the resonant wave-7 pattern. Notably, the wave train is especially active at mid-latitudes but barely affects northern Europe. Compared with anticyclones embedded in the zonal wave train, atmospheric blockings have a larger spatial scale (Rex 1950, Dole and Gordon 1983, Luo et al. 2014b), which can be applied to study weather conditions at both high- and mid-latitudes in Europe. A wide range of studies have pointed out that summer heatwaves in continental Europe are closely associated with atmospheric blocking (Trigo et al. 2005, Demirtas 2018, Dong et al. 2018, Schaller et al. 2018). In addition, Drouard et al. (2019) found that the North Atlantic Oscillation (NAO+) and a wave-7 pattern together contributed to the anomalous hot weather over northwestern Europe.

From July to early August 2018, a long-lived heatwave happened in Europe, with a large spatial scale that covered both mid- and high-latitudes. Temperatures inside the Arctic Circle topped 30 °C, while Badufoss in Norway and Kevo in Finland witnessed record-breaking temperatures of 33.5 °C and 33.4 °C, respectively (NOAA 2019). When averaged over all of France, that country experienced more than 10 minimum overnight temperatures above 20.0 °C in July, which also set a new record (World Meteorological Organization (WMO) 2018). These extreme high temperatures led to water shortages, forest fires, harvest losses, poor agricultural production, and increased mortality among elderly people (WMO 2018). Considering the large meridional spatial scale of the heatwave, one of our aims here is to determine to what extent the heatwave was related to atmospheric blocking over Europe.

In connection with a related aim, previous studies have found that the positive phase of the NAO+ events favor the occurrence of European blocking (EB) events (Shabbar et al. 2001, Scherrer et al. 2006, Croci-Maspoli et al. 2007, Yao et al. 2016). This has been demonstrated by a nonlinear multiscale interaction model developed by (Luo et al. 2015a, 2015b). The NAO has a similar spatiotemporal scale as atmospheric blocking, and it leads EB event formation by 1–3 d (Yao and Luo 2015). However, there is no one-to-one correspondence between NAO+ events and EB events, and the latter can also form through the incoming wave activity flux of a wave train (Nakamura et al. 1997). Luo et al. (2015a) proposed that EB events associated with NAO+ are stronger and more persistent in eastern Europe and are associated with intensified zonal winds and storm track over the North Atlantic. The intensified and longer-lived EB event causes more intense and more widespread extreme cold events over its downstream areas in winter, namely the southeast of Europe and the Middle East (Luo et al. 2014a, Yao et al. 2016). Since the EB event directly controls Europe and plays an essential role in the summer heatwaves in Europe, we propose that the EB event related to NAO+ might also affect some characteristics of the summer heatwave in Europe.

Following this introduction, the data and methods used for this study are described in section 2. The heatwave that happened in July and early August 2018 is analyzed in section 3. In section 4, we compare high temperatures controlled by EB events related to NAO+ and unrelated to NAO+ in order to obtain a full understanding of the relationships among EB events, the NAO+ pattern, and heatwaves. To verify the results drawn from the observational and reanalysis data, similar calculations using CMIP6 historical simulations are also performed in this section. Conclusions and discussion are provided in section 5.

2. Data and methods

2.1. Data

The daily maximum surface air temperature (MSAT) and daily precipitation data used in this study are from the European Climate Assessment and Dataset (E-OBS 19.0) with a 0.25° × 0.25° spatial resolution (Cornes et al. 2018). The daily geopotential height (Z500) and zonal wind (U500) at 500 hPa, and horizontal wind components (U850, V850) and temperature (T850) at 850 hPa are obtained from the ERA-Interim reanalysis dataset (Dee et al. 2011) at a 2.5° × 2.5° spatial resolution. The area (10°W–45°E, 40°N–75°N) is chosen to study European heatwaves, the study period spans from 1979 to 2018, and only boreal summer (June, July and August) is considered. The anomalies for daily variables are calculated by removing the climatological mean for 1979–2018 of each calendar day. We also used one historical simulation (r1i1p1f1) each from a group of 15 Coupled Model Intercomparison Project 6 (CMIP6) models (table S1) from 1980 to 2010, including the daily evolutions of Z500, U500 and surface air temperature (SAT).

2.2. Methods

The blocking action center over Europe has its greatest frequency in the summer season (Diao et al. 2006), indicating that atmospheric blocking plays a key role in modulating the summer weather extremes.
in Europe. To identify blocking events over Europe, the detection method of Tibaldi and Molteni (1990) (the TM index) is applied. This is a one-dimensional blocking detection method based on the reversal of the Z500 meridional gradient. The method can also identify the longitudinal range and duration of blocks. The specific steps in the TM method are:

(i) One-dimensional blocks: The meridional gradients of Z500 (GHGS and GHGN (referring to geopotential height gradients in the middle and high latitudes respectively)) at a particular longitude are calculated as:

\[
GHGS = \frac{Z500(\varphi_S) - Z500(\varphi_N)}{\varphi_S - \varphi_N},
\]

\[
GHGN = \frac{Z500(\varphi_N) - Z500(\varphi_S)}{\varphi_N - \varphi_S},
\]

where \( \varphi_S = 80^\circ N + \Delta, \varphi_N = 40^\circ N + \Delta, \) and \( \varphi_N = 60^\circ N + \Delta, \) and \( \Delta = -5^\circ, 0^\circ \) or \( 5^\circ. \) If \( GHGS > 0 \) and \( GHGN < -10 \) gpm (deg. lat.)\(^{-1} \) for any one of the three values of \( \varphi, \) blocking is defined to have happened at this longitude.

(ii) Blocking event: When more than five contiguous meridian lines (equivalent to 12.5 longitude degrees) are blocked in the region \( 0^\circ-60^\circ E \) for a day and this condition persists for at least 3 consecutive days, an EB event is detected.

(iii) Blocking intensity and lifetime: The blocking intensity is defined following Luo et al (2018b) and Li et al (2019, 2020a). The maximum domain-averaged Z500 anomaly for all possible positionings of a 15\(^\circ\) lon. \( \times 10^\circ \) lat. rectangle within the region \( (10^\circ E-50^\circ E, 50^\circ N-80^\circ N) \) is defined as the daily blocking intensity. During a blocking event, the day with the maximum blocking intensity is defined as the Lag 0 day. Similar to (Li et al, 2019), the lifetime of a blocking is defined by the number of consecutive days with intensities greater than 120 gpm.

The observed NAO index is obtained from the National Oceanic and Atmospheric Administration/Climate Prediction Center (www.cpc.ncep.noaa.gov). It is defined as the leading Rotated Principal Component Analysis (RPCA) mode of the Z500 anomalies. In a similar fashion, the NAO index for each CMIP6 simulation is defined as the leading Rotated Empirical Orthogonal Function (REOF) mode of Z500 anomalies over the North Atlantic region \( (90^\circ W-40^\circ E, 20^\circ N-80^\circ N) \) (Wilks 2006). To enable easy comparison, the corresponding principal components of each leading REOF mode are standardized by daily means and standard deviations of the period 1980–2010. An NAO\(^+\) event is defined as one in which the daily NAO index is equal to or greater than \(+1\) standard deviation (Std. Dev.) and persists for at least 3 consecutive days (Luo et al 2015a, 2015b; Yao and Luo 2018). An EB event is regarded as related to an NAO\(^+\) event if the Lag 0 day of the EB event lies within the lifetime of an NAO\(^+\) event; otherwise, the EB event is NAO\(^+\)-unrelated (Yao and Luo 2018).

Before identifying heatwaves, the linear trend of the MSAT anomalies at each grid point is removed. Since the main purpose of this study is to examine the relationship between large-scale atmospheric circulations (blocking highs and NAO\(^+\) events) and European heatwaves, we define the heatwaves in terms of the land-only and area-weighted average of MSAT anomalies in the European region (MSAT index, referred to as MSATI hereafter). One advantage of this approach is that it reduces or removes the effects of mesoscale or smaller weather systems. A heatwave is defined to occur when the daily MSATI exceeds the 90th percentile of the daily MSATI, calculated on a 31-day window centered on this calendar day for the base period 1981–2010, and persists for at least three consecutive days. The daily MSATI is taken as the daily heatwave intensity (Rocha et al 2020, Sulikowska and Wypych 2020). The daily spatial area of a heatwave is defined as the sum of areas with daily MSAT anomalies larger than the 95th percentile, calculated as the MSATI, at a 0.25\(^\circ\)lat/lon grid box (Russo et al 2015, Schaller et al 2018). Heatwaves in the CMIP6 historical simulations are detected in the same way as above but using SAT anomalies.

3. Collaborative circulations associated with the extreme hot Europe in summer 2018

July and early August 2018 is marked by anomalous high temperatures in northern and western Europe, while central and southern Europe are characterized by negative MSAT anomalies (figure 1(a)). To investigate the atmospheric circulations for this period in 2018, we composite the Z500 and Z500 anomalies for the period of 1 July–10 August 2018 (figure 1(b)). An NAO\(^+\) pattern over the North Atlantic and a blocking high controlling Europe are dominant in figure 1(b). The cyclonic and anticyclonic centers of the NAO\(^+\) pattern are situated over Baffin Bay and the Gulf Stream Extension, respectively, while the blocking high shows a north–south dipole mode, with a strong large-scale anticyclone over northern Europe and a much weaker cyclone over the Caspian Sea. We remark that Simmonds and Govekar (2014) have pointed to the Extension region as being a key location for driving teleconnection patterns across the Arctic and on to Europe.

According to the heatwave definition in section 2, two heatwaves of 16–20 July and 29 July–2 August occur in the period of interest. We present the daily intensity and spatial area of the heatwaves in figures 1(c) and (d). Peaks of the two heatwaves occur on 17 July and 1 August, with daily heatwave intensities of 2.89 K and 4.40 K, which are above the 95% percentile and 99% percentile, respectively. One weaker peak between the two heatwaves occurs on 25 July,
with an intensity of 2.39 K (above the 90% percentile). Correspondingly, the time series of the spatial area also shows three peaks, on 17 July, 25 July and 31 July, and the largest spatial area reaches 2.27 million km² on 31 July. Furthermore, one blocking event and three NAO+ events can be identified according to the definitions in section 2. The blocking event has a lifetime of 19 d during 16 July–3 August. Two peaks are apparent in the daily variation of the blocking intensity, which match well with the timing of the peaks of the daily heatwave intensity (figure 1(e)). In addition, three NAO+ events occur during 1 July–10 August (figure 1(f)). The first NAO+ event, during 5–11 July, leads the first peak of both the blocking and the heatwave, by 9 and 8 d, respectively, while the second NAO+ event, during 21–27 July, leads the second peak of the blocking and the second heatwave by 6 and 7 d, respectively. Notably, the third NAO+ event, during 1–5 August, happens during the decay of the blocking event and the second heatwave.

From the above results, we can see that the two heatwaves during July and early August 2018 were largely dominated by a long-lived EB event, and the blocking intensity variation was similar to the variations of the heatwave intensity and spatial area. NAO+ events were active throughout the lifetime of the EB event and the heatwaves. According to Luo et al (2015a, 2015b), the NAO+ circulation over the North Atlantic can modify the stability and persistence of EB events through changing the upstream zonal wind and storm track. The collaborative role of NAO+ and EB circulations has been examined in terms of cold extremes in winter (Luo et al 2014a, Yao et al 2017). Based on the findings above, we are encouraged to use composite analyses, to understand the characteristics of heatwaves linked to NAO+-related EB events across our period of record. As an important confirming component of our analysis it is very valuable to demonstrate that these associations are also represented in the CMIP6 model simulations.
This can lead us to construct a robust conceptual model of the relationship between heatwaves, blocking events and NAO$^+$ events, which has seldom been analyzed in previous studies.

4. Composite analyses of collaborative atmospheric circulations

4.1. NAO$^+$ events, EB events and associated heatwaves

From the definitions in section 2, 52 heatwaves, 101 NAO$^+$ events, and 115 EB events are identified over the 40-year period 1979–2018. Among the EB events, the numbers of NAO$^+$-related and the NAO$^+$-unrelated cases are 8.25 and 20.5 per decade, respectively. The number of the NAO$^+$ events without related EB events is 17.00 per decade. To examine whether the heatwaves are related to the specific circulation modes highlighted here, we have used the following terminology: if the Lag 0 d of a heatwave occurs within the lifetime of an atmospheric circulation event (an EB event or an NAO$^+$ event), this heatwave is related to a certain atmospheric circulation. The numbers (frequencies) of heatwaves that are linked to only NAO$^+$ events (without related EB events), NAO$^+$-unrelated EB events, and NAO$^+$-related EB events are 2.25 per decade (13.24%), 4.75 per decade (23.17%) and 3.75 per decade (45.45%), respectively (table 1). The frequency herein refers to the possibility of a heatwave occurring under the condition of an NAO$^+$/EB event. This suggests that an NAO$^+$ event of itself is not conducive to the formation of a European heatwave, and the lifetime (4.33 d), intensity (3.04 K) and area ($1.77 \times 10^6$ km$^2$) for related heatwaves are also the lowest. In comparison, for NAO$^+$-unrelated EB events, 23.17% of them are linked to heatwaves whose lifetime (5.00 d), intensity (3.38 K) and area ($1.95 \times 10^6$ km$^2$) are higher. Among the three circulation patterns, an NAO$^+$-related EB event is the most favorable for the occurrence of a heatwave, and the related heatwave is longer-lived (6.87 d), more intense (3.64 K), and more widespread ($1.97 \times 10^6$ km$^2$) than that of the other two types. Notably, there remains nine heatwaves that are not related to either NAO$^+$ or EB events. Boschat et al (2016) reminded some caveats when performing composite analyses to form physical hypotheses on climate connections. From what they highlighted (Boschat et al 2016), we propose that European heatwaves are more likely to correspond to a NAO$^+$/blocking (necessary condition). However, this does not establish that when you have a NAO$^+$/blocking you are more likely to have a European heatwave (sufficient condition). Some other circulation patterns (e.g. the wave trains) as well as the land surface characteristics (e.g. the soil water deficit) also contribute to European heatwaves. Thus, further comparisons concerning these nine heatwaves are not conducted in this study. Then, we evaluate the lifetime, spatial area and intensity of heatwaves simulated by 15 CMIP6 models against the observations. Generally, for the multimodel mean (MMM), NAO$^+$-related EB event has the most frequent, longest, strongest and most widespread related heatwaves, which is in good agreement with the observations. However, the MMM slightly overestimates the lifetime and spatial area of the simulated heatwaves, while underestimates the intensity of the simulated heatwaves. In the next subsection, the spatial and temporal variations of daily temperatures and atmospheric circulations associated with NAO$^+$-related EB events and NAO$^+$-unrelated EB events are further compared in order to understand the different characteristics of their related heatwaves.

4.2. Spatial and temporal variations of daily temperatures

Figures 2(a)–(c) show the composite MSAT anomalies on the Lag 0 d of NAO$^+$-related EB events and NAO$^+$-unrelated EB events, together with their differences. Positive MSAT anomalies of NAO$^+$-related EB events stretch from northern Europe to western Europe, while the east part of southern Europe exhibits negative MSAT anomalies (figure 2(a)). The largest positive MSAT anomalies are located in the northern parts of Norway, Sweden and Finland. By contrast, positive MSAT anomalies are weaker and mainly concentrated over the northern part of Europe for NAO$^+$-unrelated EB events (figure 2(b)). Figure 3(b) verifies that NAO$^+$-related EB events are associated with much warmer regions over the northern and western Europe and cooler regions over southeastern Europe when compared with NAO$^+$-unrelated EB events. The spatial distribution of SAT anomalies in the MMM is in good agreement with the observations (figures 2(d)–(f)). For each of the 15 CMIP6 models, the SAT anomalies simulated by BCC-ESM1, CESM2 and MPI-ESM1-2-HR are closer to the observations (figure S1 (available online at https://stacks.iop.org/ERL/15/114003/mmedia)). BCC-CSM2-MR, MPI-ESM1-2-LR and NorESM2-MM models show a large underestimation of positive differences in SAT anomalies in northern Europe, while ACCESS-CM2, CESM2-WACCM, EC-Earth3 and MIROC6 models underestimate the positive differences in SAT anomalies in southwestern Europe (figure S1(c)). The remaining models exhibit small differences in SAT anomalies in both regions (figure S1(c)). The time series of intensity and spatial area of SAT anomalies related to EB events are also analyzed following the relevant definitions of heatwaves in section 2 (figures 2(g) and (h)). The lifetime of the high temperature is defined as the number of days with MSATI above the 90th percentile. Five thousand subsets, each containing 33 (82) random days in the summers of 1979–2018, are produced. The 90th percentile is calculated by the averaged MSATI of the 5000 Monte Carlo subsets. Figure 2 shows that the differences for
Figure 2. Composites of MSAT anomalies (shading; units: K) for the (a) NAO$^+$-related EB events, (b) NAO$^+$-unrelated EB events, and (c) their difference on Lag 0 d derived from the E-OBS 19.0. Black (grey) stippling indicates MSAT anomalies above the 95% (90%) confidence level based on a Monte Carlo test. (d)–(f) as in figures 2(a)–(c) but for the MMM of CMIP6 historical simulations. Daily time series of the composite (g) intensity and (h) spatial area of high temperatures for NAO$^+$-related EB events (red) and NAO$^+$-unrelated EB events (blue) from Lag −10 to Lag 10 derived from the E-OBS 19.0. Lag 0 denotes the day with the largest blocking intensity. The red (blue) dashed line represents the 90th percentile of the composite (g) intensity and (h) spatial area of high temperatures, and the red (blue) marks indicate days with the composite (g) intensity and (h) spatial area above the 90th percentile for NAO$^+$-related EB events (NAO$^+$-unrelated EB events). The green (light green) shading highlights the significant differences between the two EB types above the 95% (90%) confidence level based on a Monte Carlo test for the composite (g) intensity and (h) spatial area of high temperatures. Red (blue) solid lines in (i and j) as in figures 2(g) and (h) but for the MMM of CMIP6 historical simulations. Light red (blue) band shows 10th–90th percentile of model range for NAO$^+$-related EB events (NAO$^+$-unrelated EB events) of the MMM (i) intensity and (j) spatial area. The red and blue dots indicate the significant differences between the two EB types above the 95% confidence level based on a Monte Carlo test for the MMM (i) intensity and (j) spatial area of high temperatures. All Monte Carlo tests were performed with 5000 simulations.
As known from previous studies, heatwaves are usually related to an atmospheric blocking system. The observational and model analyses above further suggest that EB events related to the NAO$^+$ pattern can cause heatwaves with larger scope, stronger intensity, and longer lifetime. Notably, the 2018 heatwave discussed in section 3.3 has a similar spatial distribution of MSAT anomaly as that in the composite NAO$^+$-related EB events, and this heatwave is closely associated with three NAO$^+$ events. This further implies the important role of collaborative impacts of EB events and the NAO$^+$ pattern in European heatwaves.

4.3. Synoptic evolutions of the atmospheric circulations

We first compare the daily variations of atmospheric circulations associated with NAO$^+$-related EB events and NAO$^+$-unrelated EB events from reanalysis and model simulations. We then set out to explain the MSAT anomalies based on these atmospheric circulations, in section 4.4. Daily Z500 and Z500 anomaly fields in reanalysis of these two types are composited from Lag −8 to Lag 8 (figure 3). In figure 3(a), an NAO$^+$ pattern over the North Atlantic is clearly apparent at Lag −8, with a strong cyclone over the Greenland and a wide anticyclone situated from the Gulf Stream extension to Europe. A weak Z500 ridge is situated over Europe and the related surface warming is dispersive. From Lag −6 to Lag 0, the weak Z500 ridge evolves to be a strong blocking system with meridional Z500 reversals. The Z500 ridge as well as the blocking anticyclone tend to have a northeast-southwest direction, especially after Lag −2, and a trough is accompanied to their southeast, where cold anomalies tend to occur. Correspondingly, significant MSAT anomalies control northern Europe and western Europe, while the east part of southern Europe has significant negative MSAT anomalies. At Lag 0, the composite blocking high reaches its maximum intensity, together with the more intense warming in Europe, whereas the NAO$^+$ pattern is getting weaker. After Lag 0, the blocking high begins to decay and move westward.

For EB events unrelated to NAO$^+$, no NAO$^+$ signals can be identified from Lag −8 to Lag 8 over the North Atlantic region (figure 3(b)). A weak anticyclone forms at Lag −6, which is situated to the east of northern Europe, and high temperatures form at very small regions. From Lag −4 to Lag 0, the anticyclone develops to be a blocking system, which shows a west-east symmetric ‘Ω’ structure at Lag 0. Corresponds with the shape of the blocking high, the blocking anticyclone mainly controls the north part of Europe, where significant positive MSAT anomalies occur. At the same time, a trough forms to the southwest of the ridge of blocking at Lag −2, and it gradually moves to the south of the ridge at Lag 0, which corresponds to the negative MSAT anomalies in southern Europe. Starting from Lag 2, the blocking anticyclone quickly moves towards the west and eventually controls the Greenland at Lag 6. Compared with figure 3(a), this blocking anticyclone moves more quickly and follows a more northerly path.

The main differences in the daily variations of atmospheric circulations for NAO$^+$-related EB events and NAO$^+$-unrelated EB events are well reproduced by model simulations (figure 4). The NAO$^+$ pattern occurs prior to the formation of EB related to NAO$^+$, indicating that NAO$^+$-related EB events are mainly formed by the energy dispersion from the upstream NAO$^+$, while the upstream circulations for NAO$^+$-unrelated EB events are too weak to discern.

Table 1. Number of NAO$^+$-related EB events, NAO$^+$-unrelated EB events and NAO$^+$ events without EB, and characteristics (number, frequency, average lifetime, average spatial area, and average intensity) of related heatwaves derived from E-OBS 19.0. (These numbers are expressed as events per decade.) The frequency of heatwave refers to the possibility of a heatwave when a NAO$^+$/EB event occurs. The comparable numbers for the mean of the CMIP6 historical simulations are presented in parentheses. The periods covered are 1979–2018 and 1980–2010 for E-OBS 19.0. and CMIP6 historical simulations, respectively.

|                | NAO$^+$ events without EB | NAO$^+$-unrelated EB events | NAO$^+$-related EB events |
|----------------|---------------------------|-----------------------------|---------------------------|
| Number of NAO$^+$/EB events (/decade) | 17.00 (18.95) | 20.50 (15.46) | 8.25 (7.20) |
| Number of heatwaves (/decade) | 2.25 (1.85) | 4.75 (4.88) | 3.75 (2.86) |
| Frequency of heatwaves | 13.24% (9.76%) | 23.17% (31.57%) | 45.45% (39.72%) |
| Average lifetime of heatwaves (days) | 4.33 (5.00) | 5.00 (5.59) | 6.87 (6.90) |
| Average spatial area of heatwaves ($10^6$ km$^2$) | 1.77 (2.10) | 1.95 (2.30) | 1.97 (2.32) |
| Average intensity of heatwaves (K) | 3.04 (2.78) | 3.38 (3.01) | 3.64 (3.27) |
Figure 3. Instantaneous fields of composite daily Z500 (black contours, interval = 30; units: gpm), positive (violet) and negative (green) Z500 anomalies (contours, interval = 15; units: gpm) and MSAT anomalies (shading; units: K) from Lag $-8$ to Lag 8 for (a) NAO$^+$-related EB events and (b) NAO$^+$-unrelated EB events derived from the E-OBS 19.0 and ERA-interim. The thick yellow lines denote the tilt of the composite EB events on Lag 0 d. Only regions with MSAT anomalies above the 95% (90%) confidence level based on a two-sided Student’s $t$-test are plotted.

In addition, EB events of these two types have different shapes; the blocking ridge of NAO$^+$-related (NAO$^+$-unrelated) EB events show a northeast-southwest (north-south) distribution with a more southeastward (southward) trough. Also, NAO$^+$-unrelated EB events seem to be more mobile and have a more rapid westward movement during the dissipating stage.

4.4. Collaborative role of atmospheric circulations and its linkage with heatwaves

We now relate the different characteristics of high temperatures with atmospheric circulations for NAO$^+$-related EB events and NAO$^+$-unrelated EB events. The time-longitude evolution of composite Z500 anomalies averaged over 55°–65°N (52.5°–62.5°N) for NAO$^+$-related (NAO$^+$-unrelated) EB
Figure 4. As in figure 3 but for the MMM of CMIP6 historical simulations.

events is shown in figure 5(a) (figure 5(b)). The Z500 anomaly has its largest value of 128.33 gpm for NAO\(^+\)-related EB events, which is stronger than that (85.64 gpm) of NAO\(^+\)-unrelated EB events. Additionally, the composite Z500 anomaly larger than 50 gpm persists for 7 d for NAO\(^+\)-related EB events, which is 2 d longer than in the NAO\(^+\)-unrelated case. We also calculate the slopes of arrows that denote the travelling speeds of composite EB events. The composite NAO\(^+\)-related EB events move at a speed of 6.85 (3.00) longitude degrees per day at their forming (decaying) stage, which is nearly a half (a quarter) of the travelling speed (12.50 longitude degrees per day) of the NAO\(^+\)-unrelated EB events. These analyses suggest that the composite NAO\(^+\)-related EB events are stronger and more stable (quasi-stationarity)
Figure 5. Time–longitude evolution of daily composite Z500 anomalies for (a) NAO$^+$-related EB events and (b) NAO$^+$-unrelated EB events averaged over the latitudes 52.5$^\circ$–72.5$^\circ$N and 55$^\circ$–75$^\circ$N derived from the ERA-interim, respectively, where the thick green arrows denote the movement of the composite EB events and the thick yellow solid contours denote the value of 50 gpm. Z500 anomalies above the 95% confidence level based on a two-sided Student's t-test are denoted by stippling.

(c) and (d) as in figures 5(a) and (b) but for the MMM of CMIP6 historical simulations. Daily time series of the composite (e) NAO index and (f) upstream U500 anomalies averaged over the region (80$^\circ$W–0$^\circ$, 40$^\circ$–60$^\circ$N) for the (red) NAO$^+$-related EB events and (blue) NAO$^+$-unrelated EB events from Lag $-10$ to Lag 10. The red (blue) dashed line represents the 10th and 90th percentile of the composite (e) NAO index and (f) upstream U500 anomalies, and the red (blue) marks indicate days with the composite (e) NAO index and (f) upstream U500 anomalies outside the 10th–90th band for NAO$^+$-related EB events (NAO$^+$-unrelated EB events). Green (light green) shading highlights the significant differences between the two EB types above the 95% (90%) confidence level based on a Monte Carlo test with 5000 simulations for the composite (e) NAO index and (f) upstream U500 anomalies. Red (blue) solid lines in (g and h) as in figures 5(e) and (f) but for the MMM of CMIP6 historical simulations. Light red (blue) band shows 10th–90th percentile of model range for NAO$^+$-related EB events (NAO$^+$-unrelated EB events) of the MMM (g) NAO index and (h) upstream U500 anomalies. The red and blue dots indicate the significant differences between the two EB types above the 95% confidence level based on a Monte Carlo test with 5000 simulations for the MMM (g) NAO index and (h) upstream U500 anomalies.
over Europe. These strong and persistent blocking events could favor stronger and longer-lived heatwaves through accumulating more heat brought by increased solar radiation, warm advection, adiabatic subsidence, etc. Notably, the NAO$^+$-related EB events are even more stable during dissipation, which favors the continuous high temperatures after Lag 0 d of EB events (figures 2(g) and (h)). The simulated time–longitude evolution of composite Z500 anomalies for NAO$^+$-related EB events and NAO$^+$-unrelated EB events resembles that in reanalysis (figures 5(c) and (d)). One difference in the MMM from the reanalysis is that the movement of NAO$^+$-unrelated EB events can also be divided into two stages. The blocking anticyclone in the dissipating stage has a slower speed (5.89 longitude degrees per day) than that (3.63 longitude degrees per day) of the forming stage for NAO$^+$-related EB events, while the blocking anticyclone is more movable in the dissipating stage (17.50 longitude degrees per day) than in the forming stage (8.33 longitude degrees per day) for NAO$^+$-unrelated EB events.

One possible explanation for the differences in the intensity and movement of EB events for the two types, as described above, is in the nature of the upstream NAO pattern. The daily variations of composite NAO indices and upstream domain-averaged (80°W–0°, 40°–60°N) U500 anomalies are presented in figures 5(e) and (f). The NAO index of NAO$^+$-related EB events is significantly larger than that of the NAO$^+$-unrelated EB events during the whole study period (from Lag $-10$ to Lag 10). Specifically, the NAO index is above the 90th percentile for NAO$^+$-related EB events from Lag $-10$ to Lag 4, whereas NAO$^+$-unrelated EB events have negative NAO index values less than the 10% percentile from Lag 1 to Lag 9. Corresponding to the NAO indices, large discrepancies can also be seen in the composite U500 anomalies, where significant differences can be seen from Lag $-10$ to Lag $-2$. The increased upstream zonal wind, together with the NAO$^+$ pattern at the formation stage of the NAO$^+$-related EB events, could favor the reinforcement and persistence of EB events through strengthening the energy dispersion (Yao et al 2017, Luo et al 2018a). The simulated NAO indices and upstream U500 anomalies for NAO$^+$-related EB events also have significantly increased values prior to EB events. The peak of NAO index (upstream U500 anomaly) leads the Lag 0 d of NAO$^+$-related EB events by 1 d (4 d) in MMM, while the leading time is 4 d (5 d) in reanalysis.

In addition to their intensity and persistence, EB events also have different shapes for the NAO$^+$-related case and the NAO$^+$-unrelated case. NAO$^+$-related EB events with a northeast–southwest orientation contribute to strong and widespread southerly wind vectors to their west, and hence strong warm air advection (figure 6(a)). The southern cyclonic circulation of the blocking is situated more to the east, which brings anomalous cold air to southeastern Europe. Associated with the northeast–southwest orientated blocking, most of Europe has negative precipitation anomalies, except that the southeastern Europe has significantly increased precipitation (figure 6(a)). It is suggested that the strong warm air currents and a lack of precipitation could explain the distribution of high temperatures associated with NAO$^+$-related EB events. Compared with the large range of high temperatures for NAO$^+$-related EB events, positive MSAT anomalies are mainly concentrated in the northern part of Europe for NAO$^+$-unrelated EB events. This
could be attributable to the symmetric ‘Ω’ shape of the NAO⁺-unrelated EB ridge. The anticyclonic circulation and warm airflow only control the north part of Europe, while the cyclonic circulation which could increase precipitation situated over the south part of Europe (figure 6(b)). Thus, MSAT anomalies in the south part of Europe are reduced, and positive MSAT anomalies are only confined to the northern Europe. Compared with NAO⁺-related EB events, the warm wind vectors are less strong and less widespread for the NAO⁻-unrelated case, which also explains their weaker and smaller-area high temperature. These findings suggest that the shape of the blocking events could further impact the intensity and scope of high temperatures through changing the warm airflow and precipitation.

5. Conclusions and discussion

We have shown that two heatwaves of July and early August 2018 were associated with collaborative atmospheric circulations involving one blocking event and three NAO⁺ events. During this period, high temperatures covered a large domain, including both northern and western Europe, where record-breaking high temperatures were recorded at many stations. Our analysis has led to the conclusion that the atmospheric blocking over Europe and the NAO⁺ pattern comprised a favorable circulation pattern for the heatwaves. This proposition was further verified by composite analyses of NAO⁺-related EB events and NAO⁺-unrelated EB events.

NAO⁺-related EB events lead to positive MSAT anomalies in both the northern and western Europe, which is similar to the spatial pattern of the summer 2018 heatwave. In comparison, the positive MSAT anomalies of NAO⁺-unrelated EB events are mainly situated in the north part of Europe. In addition, the positive MSAT anomalies are significantly stronger and more persistent for NAO⁺-related EB events. These characteristics of high temperatures are well explained by atmospheric circulations. When an EB event and NAO⁺ event occur together, the zonal wind over the North Atlantic is significantly strengthened. This can then intensify the downstream wave activity, which in turn strengthens and sustains the EB event. Thus, we can attribute strong and persistent high temperatures to strengthened and sustainable EB events. Moreover, the position and scope of high temperatures are closely related to the shape of EB events. The composite NAO⁺-related EB event with a northeast–southwest orientation increases the warm airflow in the west of the blocking anticyclone. The trough of the blocking system in this type is situated more eastward, only resulting in precipitation and lower temperatures in the east part of southern Europe. These aspects explain the large extent of the high temperatures in Europe. By contrast, the composite NAO⁺-unrelated EB events without orientation is accompanied by a trough over the south part of Europe, which promotes positive precipitation anomalies in southern Europe. As a result, the high temperatures of NAO⁺-unrelated EB events concentrate in the northern part of Europe only. We note that the main results in this study concerning the relationships between temperatures and atmospheric circulations are in close agreement with those revealed in CMIP6 simulations, indicating that the conclusions derived from the observations and reanalysis are physically meaningful and robust.

Previous studies have tended to only consider the role of blocking events in the occurrence of European heatwaves (Trigo et al 2005, Demirtas 2018, Dong et al 2018, Schaller et al 2018). In this study, we further reveal that, combined with the NAO⁺ pattern, the lifetime, magnitude and spatial scope of heatwaves can be increased through changed behavior and an altered shape of the blocking system. Moreover, it is found that the composite NAO event leads the EB event by 4 d from reanalysis (figure 5(e)), and the MSAT anomaly decay lags the most intensive blocking day by 1 d. These potential precursors can aid the preparedness for intense and long-lived heatwaves to several days in advance. In particular, when an EB event and the NAO⁺ pattern occur concurrently, countries in southwestern Europe should be placed on alert. Since the NAO index is also characterized by variations on interdecadal/decadal timescales, and can be predicted from the sea surface temperatures (SSTs) in the North Atlantic (Higuchi et al 1999), it may be possible to estimate the number, extent and magnitude of heatwaves in the future through the state of the North Atlantic SSTs and NAO index.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
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