Asymmetry of Winter European Surface Air Temperature Extremes and the North Atlantic Oscillation

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ABSTRACT

Interannual variations of winter warm and cold extremes in Europe are investigated. It is found that the variations are closely connected to the phase of the North Atlantic Oscillation (NAO). The leading EOF of the winter cold (warm) surface air temperature (SAT) extreme frequency shows an enhanced occurrence over western (eastern) Europe. The SAT probability distribution function of the cold extreme winter exhibits both a decrease of the mean SAT and a marked increase in SAT variance, whereas it shows only a shift of the mean SAT to the warmer side for extreme warm winters.

This study reveals an asymmetry in location between the cold and warm extremes, caused by the NAO modulations of blocking events and other submonthly variations. Winters with frequent cold extremes are mainly accompanied by the eastern Atlantic blocking. The circulation causes not only marked local cooling but also increased SAT gradient, resulting in both enhanced SAT variance and increased occurrence of cold extremes. By contrast, winters with frequent warm extremes are associated with the northeast–southwest tilted positive NAO pattern. The warm advection by the submonthly perturbations is responsible for the development of warm extremes. The reduced SAT gradient due to enhanced warm advection weakens SAT variance over northern Europe. Thus, the cold extremes are larger in terms of deviations from the monthly mean than the warm extremes.

1. Introduction

Weather extremes draw huge amounts of attention because of their large societal impacts and economic costs. Many studies have linked weather extremes to global warming and large-scale atmospheric circulations (Alexander et al. 2006; Croci-Maspoli and Davies 2009; Sillmann and Croci-Maspoli 2009; Sillmann et al. 2011). Alexander et al. (2006) presented a global picture of trends in extreme temperature and precipitation indices and found widespread changes in temperature extremes associated with a positive shift in the distribution of daily minimum temperatures throughout the globe. Ito et al. (2013) showed that the surface air temperature (SAT) extremes over East Asia to first order follow the seasonal mean variability, and the asymmetry between cold and warm extreme days is due to the change in the shape of the probability distribution function (PDF). Temperature extremes are substantially affected by large-scale circulation patterns and climate variability. Scaife et al. (2008) found that the change in extreme winter weather events over Europe is due to a long-term change in the North Atlantic Oscillation (NAO). The negative phase of NAO is related to the Greenland blocking (Luo et al. 2007; Woollings et al. 2008), which is responsible for extreme cold temperatures and associated with the eastern Atlantic blocking. The circulation causes not only marked local cooling but also increased SAT gradient, resulting in both enhanced SAT variance and increased occurrence of cold extremes. By contrast, winters with frequent warm extremes are associated with the northeast–southwest tilted positive NAO pattern. The warm advection by the submonthly perturbations is responsible for the development of warm extremes. The reduced SAT gradient due to enhanced warm advection weakens SAT variance over northern Europe. Thus, the cold extremes are larger in terms of deviations from the monthly mean than the warm extremes.
in the European continent and its adjacent regions (Trigo et al. 2004; Sillmann and Croci-Maspoli 2009; Sillmann et al. 2011). Wettstein and Mearns (2002) revealed significant increases in frequency of maximum temperature extremes during winter in New England and in minimum temperature extremes during spring in Quebec for high NAO–Atlantic Oscillation (AO) index years. Fereday et al. (2012) indicated that the extreme low NAO index in winter 2009/10 contributed to cold conditions over large areas of Eurasia and North America. These studies indicate a significant relationship between the NAO and the SAT extremes on interannual time scales over the broad region of North America, the Atlantic, and Eurasia.

While the NAO exhibits intraseasonal, interannual and decadal time-scale variations (Hurrell 1995), the typical lifetime of individual NAO events is of about two weeks (Feldstein 2003; Benedict et al. 2004). The intraseasonal blocking and NAO events are associated with feedback from transient synoptic-scale eddies (Shutts 1983; Feldstein 2003; Luo 2005). During a blocking or positive NAO event, synoptic-scale eddies are steered and deformed by the planetary-scale flow (Luo 2005; Luo et al. 2007).

In light of the fact that NAO variability covers a wide range of time scales from subseasonal to seasonal, we examine how the multiscale nature of NAO affects SAT extreme occurrence, an important aspect of atmospheric dynamics that has not been fully explored in the study of the extremes. We show contributions of individual NAO events and changing seasonal mean SAT to the winter SAT extreme occurrence over the Europe/Atlantic sector. We further demonstrate that the asymmetry of the cold and warm extremes is linked to the subseasonal atmospheric variations. By exploring the connections between the submonthly/transient time-scale variations and the winter SAT extremes, we shed light on the cause of the cold and warm extremes.

The paper is arranged as follows. Section 2 describes data and methodology. Section 3 presents the regional distributions of temperature extremes in the Europe/Atlantic sector. The interannual variability of European SAT extremes and its relationship to the multiscale SAT variations from the winter mean are also discussed. Section 4 examines the impacts of submonthly and transient atmospheric variability on local SAT extremes and the contribution of thermal advection and circulation regimes to the cold and warm extremes. The asymmetry of the cold and warm SAT extremes is discussed in section 5. Conclusions and discussion are presented in section 6.

2. Data and methodology

We use the daily averaged fields of SAT, geopotential height, and velocity from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis from 1949 to 2009. The data are of 2.5° horizontal resolution at the 500-, 850-, 925-, 1000-hPa pressure levels and sea surface. The annual cycle and the linear trend are removed from the original daily gridpoint data. The daily data for winter from December to February (DJF) are then divided to the synoptic-scale transient (2–7 days) and submonthly-scale (7–31 days) processes using a bandpass filter.

The warm and cold extremes are percentile-based indices (Alexander et al. 2006) developed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI; http://www.wmo.int/pages/prog/wcp/wcdmp/CA_3.php). Based on the ETCCDMI extreme index, the cold/warm extreme threshold is calculated as the 95th (5th) percentile of the descending sorted daily temperature of all the 50 years of winter DJF months. The cold/warm extreme is defined when the SAT is equal to or exceeds the extreme threshold. A regional mean monthly temperature extreme frequency index (REI) is defined based on the first empirical orthogonal functions (EOFs) of the monthly frequency of the cold/warm extremes. The REI is detrended first and variations longer than decadal are removed from the detrended REI using a high-pass filter, since our attention is focused on time scales from the synoptic to interannual. The local extreme event is also defined as the temporal evolution of the SAT extreme on given grid points. Moreover, a $k$-means algorithm (Anderberg 1973) is used to identify the 500-hPa height circulation regimes associated with SAT extreme events.

3. Spatial distributions and relationship with multiscale SAT variations

a. Spatial distributions and interannual variations

To extract the spatial distribution of the winter SAT extremes, the EOFs of local cold/warm extreme frequency for winter month are calculated in the Europe/Atlantic sector (from 100°W to 60°E). As shown in Fig. 1, the leading EOFs of cold and warm extremes reveal two main action centers: one over Baffin Bay and the other over Europe with opposite signs. The large loading of the cold extreme variability over Europe is found in the region from the English Channel to Poland. By contrast, the major action center of the warm extremes over Europe is located more eastward and exhibits a meridional dipole structure with a zero line near 40°N. This is similar to the result of Kenyon and Hegerl (2008), who noted that there are increased warm days in northeast Europe and decreased cold days mainly over northwest Europe during the positive phase of NAO.
Although the leading EOFs reflect the spatial distribution of the winter cold/warm extremes variation over Europe, it can explain only about 10% of the total variance over the large analysis domain. But the main loading can explain a larger variance over the local region. When the EOF calculation is performed over a small domain of Europe, similar EOF modes to those in Fig. 1 explain nearly 30% of the total variation for both cold and warm extremes. Thus it is reasonable to define a regional mean monthly temperature extreme frequency index based on the main loading of the first EOFs. Based on the first EOFs of the extreme frequency, the white rectangle regions in Fig. 1 (50°–57.5°N, 0°–25°E for cold extremes and 55°–62.5°N, 15°–45°E for warm extremes) are chosen to calculate the REI. The REI (shown in Fig. 2) is calculated by averaging the monthly extreme frequencies over each region. The REI is representative of the extreme frequency variability over Europe and is similar to the leading principle component (PC1) of the extreme frequency.

The interannual variability of the SAT extreme is notable (Fig. 2). The cold and warm REIs exhibit a negative correlation of −0.41. The interannual variation of the winter NAO index correlated with the cold (warm) REI at −0.58 (0.38). So the negative (positive) NAO pattern is associated with more cold (warm) SAT extremes over Europe, with the region of enhanced warm extreme occurrence shifting eastward compared to the region of the enhanced cold extreme occurrence (Fig. 1). Besides SAT extremes over Europe, NAO also affects the SAT extremes over northeast Canada; similar warm (cold) REIs defined for northeast Canada show significant correlations with NAO. The results indicate that the interannual variations of the SAT extreme occurrences over both the regions around Baffin Bay and Europe are strongly influenced by the NAO, but with opposite effects. As the correlation between the NAO index and the cold (warm) REI is −0.58 (0.38), the seasonal mean NAO pattern is not the only mechanism.

b. Effects of seasonal mean and subseasonal variance

Before discussing the impacts of NAO events on winter cold and warm extremes over Europe, we first inspect the relationship between the variations of the winter SAT extremes and the winter mean/subseasonal variance of SAT. A cold (warm) extreme winter is defined if the DJF mean cold (warm) REI is greater than the climatology (REI > 0), while normal winter is defined when the DJF

![Fig. 1. First EOFs of the monthly frequency of the daily (a) cold and (b) warm extreme occurrences.](image1)

![Fig. 2. Variation of the monthly frequency of regional mean daily (a) cold and (b) warm SAT extreme occurrences, with the low-frequency variation (10 years or longer) removed by a high-pass filter.](image2)
mean warm and cold REIs are both less than 0. The PDF of the daily winter SAT for the normal winters and the cold/warm extreme winter are calculated at location 1 (Warsaw; 52°N, 21°E) and location 2 (St. Petersburg; 60°N, 30°E) (Fig. 3). The two locations are selected because they are at the action centers for the cold and warm SAT extremes, respectively (Fig. 1).

Compared to the normal winter, the PDF for the warm extreme winters shows a shift of the mean value to the warmer side with a slight increase in skewness at both locations but no significant difference in variance. For cold extreme winters, in addition to the shift of the mean value to the colder side, the SAT variance increases, especially at Warsaw. This indicates that the occurrences of winter cold extremes are related to the subseasonal variation of the winter circulation, and this relation is more robust in western Europe. The warm extremes are mainly connected to the winter mean SAT rather than the submonthly variance. A similar PDF analysis done for northeast Canada shows some difference from the result over Europe: the cold extreme winter in northeast Canada shows mainly a shift of the mean temperature to the colder side with a slight increasing of variation, while the warm extreme winter in northeast Canada shows both increase in variance and a shift of mean temperature to the warmer side. This is consistent with the zonal dipole pattern between northeast Canada and Europe.

Since the life cycle of individual NAO events is typically two weeks and is associated with transient eddies, the subseasonal variations considered in the present study are mainly of the submonthly (7–31 days, the time scale of blocking and NAO events) and transient time scales (2–7 days, synoptic scale transients). The REIs of the cold (warm) extremes are negatively (positively) correlated with the winter mean SAT (Fig. 4). The correlation coefficient pattern resembles the leading EOFs of SAT extreme frequency over the Atlantic/Europe.
sector. It is also similar to the winter NAO-related SAT pattern. This indicates that the occurrence of the cold and warm extremes is affected by the NAO-related seasonal mean SAT. While the seasonal mean SAT pattern looks symmetric, the leading EOFs of the cold and warm extreme frequencies show a strong asymmetry (Fig. 1). The large loading is over the western part of Europe for the cold extremes but over the eastern part of Europe for the warm extremes.

Figure 5 shows the correlation coefficient between the REI and the transient/submonthly SAT variance. The cold REI is positively correlated with the transient and submonthly variability of winter SAT over the major part of Europe. The most significant region is located over the western part of Europe (Figs. 5 a–b). The warm REI is negatively correlated with both the transient and submonthly variances of SAT over Europe, but the correlations are weaker and less extensive in space than those for the cold REI. This indicates that the increase of warm extremes occurrence is not related to the enhanced transient/submonthly fluctuations, whereas it is significantly related to an increase of winter mean temperature (Fig. 4). Thus, warm extremes are mainly due to the winter mean temperature anomalies, but cold

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**FIG. 4.** Correlation between seasonal mean SAT and REI for the (a) cold and (b) warm extremes. Thick white contours show the 95% significant confidence level.

**FIG. 5.** Correlations between seasonal variance of (a) transient and (b) submonthly variability and the cold REI. (c),(d) As in (a),(b), but for the warm extremes.
extremes result from both the decrease of the winter mean SAT and the increase of the subseasonal variance.

4. Contributions of submonthly and transient variability

This section examines how the dominant regimes, such as the NAO and blocking, contribute to the increase in the SAT variance and its impact on the SAT extremes.

a. Evolution of circulation pattern

First we examine the evolution of the circulation patterns related to the winter SAT extreme events in the Atlantic/Europe sector. The daily 500-hPa height fields are composited based on the selected cold and warm extreme events. As shown in Figs. 6 and 7, the cold (warm) extreme events are connected to the development of the eastern Atlantic blocking (positive NAO circulation). The composited 500-hPa circulation patterns corresponding to the cold and warm extremes look quite symmetric. The large-scale circulation exhibits a northwest–southeast tilted dipole structure with a high-pressure (low pressure) anomaly over the northeast Atlantic and a low-pressure (high pressure) anomaly over southern Europe. The blocking (positive NAO) circulation intensifies and shifts toward the European continent during the developing period of cold (warm) extreme events. At the lag \(-1\) day, the zonal pressure gradient reaches the maximum, with strongest northerly (southerly) flow. From lag \(0\) day, the blocking (positive NAO) circulation, and correspondingly the zonal pressure gradient, begins to weaken and retreat westward, which indicates the decay or even the reverse of cold (warm) thermal advection. The blocking (positive NAO) circulation also steers the transient eddies. As shown in Fig. 8, the correlation between the monthly cold extreme frequency and transient eddy kinetic energy (EKE) indicates the Atlantic storm track is split into a south (from the southeastern Atlantic Ocean toward the Mediterranean Sea) and north (near Greenland) branches by the blocking. The Atlantic storm track is intensified (south of Greenland toward northern Europe) during months of frequent warm extremes (corresponding to the positive
Thus, the transient thermal advection is modulated by the blocking (positive NAO) circulation as well.

b. Thermal advections during the extreme event life cycle

In this section, we calculate the local heat budget to diagnose the contributions of the submonthly and synoptic-scale transient processes in the evolution of the cold and warm extremes.

In the absence of strong diabatic heating, the rate of change of the perturbation potential temperature is

$$\frac{\partial \theta}{\partial t} = -\left(\frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y}\right) - \frac{\partial \theta_0}{\partial p},$$

(1)

FIG. 7. Composite evolution of the 500-hPa geopotential height fields for warm extreme events at location 2.

FIG. 8. Correlation between the seasonal mean 850-hPa eddy kinetic energy (shading) and the REI of (a) cold and (b) warm extremes. The white contours denote the 95% confidential level.
where $\theta$ is potential temperature and $\theta_0(z)$ is the basic state (Holton 2004). We separate all the variables in Eq. (1) into two parts: the monthly mean and the submonthly variation. The subseasonal variation here includes the 2–7-day synoptic transients and the 7–31-day low-frequency processes.

First, all the variables are separated into monthly mean and submonthly variation,

$$\frac{\partial (\bar{\theta} + \theta')}{\partial t} \approx - \left[ (\bar{\pi} + u') \frac{\partial (\bar{\theta} + \theta')}{\partial x} + (\bar{\nu} + v') \frac{\partial (\bar{\theta} + \theta')}{\partial y} \right] - (\bar{\omega} + \omega') \frac{\partial \theta_0}{\partial p},$$

$$\left(2\right)$$

Note that the time evolution of the monthly mean is

$$\frac{\partial \bar{\theta}}{\partial t} \approx - \left( \frac{\partial \bar{\theta}}{\partial x} + \bar{\pi} \frac{\partial \bar{\theta}}{\partial x} + \bar{\nu} \frac{\partial \bar{\theta}}{\partial y} + \bar{\omega} \frac{\partial \bar{\theta}}{\partial p} \right) - \bar{\omega} \frac{\partial \theta_0}{\partial p},$$

$$\left(3\right)$$

Subtracting Eq. (3) from Eq. (2), we get the submonthly evolution:

$$\frac{\partial \theta'}{\partial t} \approx - \left[ \bar{\pi} \frac{\partial \theta'}{\partial x} + \bar{\nu} \frac{\partial \theta'}{\partial y} + \frac{\partial \bar{\theta}}{\partial x} + \frac{\partial \theta'}{\partial y} \right]$$

$$+ \left[ u \frac{\partial \theta'}{\partial x} + v \frac{\partial \theta'}{\partial y} - \frac{\partial \bar{\theta}}{\partial x} - \frac{\partial \theta'}{\partial y} \right] - \omega' \frac{\partial \theta_0}{\partial p},$$

$$\left(4\right)$$

where $u'$, $v'$, and $\omega'$ include the 2–7-day (transient) and 7–31-day (submonthly) bandpass variables, and $\bar{\pi}$, $\bar{\nu}$, and $\bar{\omega}$ denote the monthly mean. The terms on the right-hand side of Eq. (4) to $\partial \theta'/\partial t$ are diagnosed at the 850-hPa level for each selected extreme event. The results for the cold and warm extreme events are composited separately based on the selected extreme events (Fig. 9).

The composite result shows that the time evolution of the potential temperature of the cold (warm) extreme events is mainly controlled by submonthly process; that is, the advection of submonthly temperature variation by the persistent blocking (positive NAO circulation) (deep blue line in Figs. 9a–b). The contributions of this term are similar in the developing stage of the cold and warm extremes but differ in the decay stages. It turns into a warming factor that causes the decay of the cold extreme event but remains a weak warm effect in the warm extreme event and prevents the warm extreme from decaying.

The cross terms, the advection of transient (submonthly) temperature variation by submonthly (transient) flow, also make important contributions to the growth of the SAT extreme but are less persistent in time. The advection of transient temperature perturbation by the submonthly flow is the leading cause of the decay of both the cold and warm extremes and is the most important reason for the decay of warm extreme.

Both the double transient terms (the advection of transient temperature perturbation by transient flow) and the cross terms involving the mean flow/temperature and the submonthly (transient) flow/temperature variation are small. The vertical thermal transport is even smaller and is not shown. Among these terms, the advection of mean temperature by the submonthly flow shows weak positive contributions to both cold and warm extreme events, while the advection of submonthly temperature variation by the mean flow has a negative effect on the cold extreme event.

5. Asymmetry between cold and warm SAT extremes

As indicated in section 3a, the interannual variation of cold and warm extremes is correlated to the NAO pattern. The correlation between the winter mean 500-hPa geopotential height and the REI (Fig. 10a) shows the background circulation of the Atlantic blocking in winters of frequent cold extremes. The winter background circulation related to the warm extreme winters (Fig. 10b) is a precursor for positive NAO events. Thus, the seasonal mean phase of the NAO modulates the interannual variability of SAT extremes by affecting the probability of submonthly perturbations.

a. Asymmetric locations of the action centers

The action center of the interannual variation of warm SAT extremes is located eastward of that of cold extremes, and the frequency of cold (warm) extremes is significantly modulated by the NAO pattern. Peterson et al. (2003) suggest a nonlinearity of NAO with the positive NAO index shifted more eastward of the negative NAO pattern. Thus, the eastward shift of the warm extremes over Europe may be explained by the eastward shift of the positive NAO itself. To verify this, we calculate the spatial distribution of the correlation between the winter mean NAO index and the frequency of the cold (warm) SAT extremes (Fig. 11). The correlation patterns resemble the leading EOFs of SAT extremes (Fig. 1) in Europe. The cold (warm) SAT extreme occurrence shows negative (positive) correlation with the NAO in northwest (northeast) Europe. This indicates that the location of the cold/warm extremes is controlled by the NAO phases. The positive (negative) NAO leads to the eastward (westward) shift of warm (cold) extremes.

Figure 12 shows the composite patterns of submonthly 850-hPa wind, 500-hPa geopotential height, and the advection of submonthly temperature variation
by submonthly flow at lag −1 day of the cold and warm extreme events. Large-scale blocking (positive NAO) circulation induces strong northerly (southerly) flow and cold (warm) advection at 850 hPa. The circulation patterns corresponding to the cold and warm extremes are quite symmetric. Yet the most significant cooling (warming) occurs in the northerly (southerly) flow region and its downstream side. Thus, even if the anomalous circulation patterns are symmetric, the cold extremes tend to locate more southward than the warm extremes. This result is

![Fig. 9. Evolution of the horizontal thermal advection and the local rate of potential temperature change (black line) at (a), (c) Warsaw (52°N, 20°E) and (b), (d) St. Petersburg (58°N, 32°E), in which advections of the potential temperature perturbation by the velocity perturbation are shown in (a), (b) and the cross terms involving the mean/perturbation of the potential temperature and the mean/perturbation of the velocity are shown in (c), (d), where the perturbation is referring to transient and submonthly variations.](image)

![Fig. 10. Correlation between the seasonal mean 500-hPa geopotential height and the REI of (a) cold and (b) warm extremes. The shading denotes the 95% confidential level.](image)
consistent with the fact that the submonthly nonlinear term, the advection of submonthly temperature variations by submonthly flow is an important term in the thermal advection budget (Fig. 9). Though the above composite results are based on the selected locations, the results do not change when the composite is based on other locations with the same sign in the leading EOFs (Fig. 1).

Next, we use the $k$-means cluster method to examine the dominant circulation regimes during extreme events. The entire collection of the lag $-1$ days of the local cold (warm) extreme events is used as samples, based on which the 500-hPa geopotential height fields are clustered. Fereday et al. (2008) show that there is no objective choice of the number of clusters $k$. We just chose an appropriately small $k$, $k = 3$ ($k = 2$) for the cold (warm) extremes collection. This choice of $k$ seems stable because we conduct the cluster many times and get similar circulation regimes with a similar number of cases within one cluster.

The 500-hPa geopotential height fields associated with cold extremes are clustered into three regimes (Fig. 13): the western Atlantic blocking (C-1), the Scandinavian blocking (C-2), and the eastern Atlantic blocking (C-3). Though the action center of the blocking high is different among the three clusters, they all have intensified low-pressure anomalies over Europe, with the enhanced zonal pressure gradient that drives an intensified northerly flow from the cold polar region to Europe, with a downstream impact on northwestern Europe.

Among all the lag $-1$ days of the cold extreme events, the Scandinavian blocking occurs more frequently than the other two clusters, occurring in 42% of the total number of events (Fig. 15a). The occurrence of the other two clusters is less frequent and of a similar probability. The eastern Atlantic blocking provides a favorable circulation condition for the occurrence of more severe cold days and is connected to the lowest cluster mean SAT (the averaging for all the lag 0 SAT in the cluster). We note that the differences between the clusters’ mean

![Figure 11](image1.png)

**Fig. 11.** Correlation between the winter mean NAO index and the frequency of (a) cold and (b) warm SAT extreme occurrences. The white contours denote the 95% confidential level.

![Figure 12](image2.png)

**Fig. 12.** Composite 500-hPa height (gray line), submonthly horizontal thermal advection (color shading), and 850-hPa wind (green arrows) based on the lag $-1$ day of (a) cold extreme events at Warsaw and (b) warm extreme events at St. Petersburg.
SAT is smaller than the variance among events in each cluster.

The 500-hPa potential height fields corresponding to the warm extreme events at location 2 are clustered into two (W-1 and W-2) regimes (Fig. 14), showing a wave train and meridional positive NAO pattern, respectively. Europe is covered by a high-pressure center in both regimes, especially for the W-2 regime. The low-pressure pattern makes the two regimes different, eastward shifted close to Europe in one and located in the central North Atlantic in the other. Both the regimes imply a strengthened southerly flow in Europe. The presence of the high-pressure anomaly upstream of the eastern Atlantic low pressure in the W-1 regime causes the northward shift of the mean storm track, in favor of reduced persistence of the positive NAO (Franzke et al. 2004). So the W-2 regime is more stable and associates with more warm extreme events. The cluster mean extreme SAT shows almost no difference between the two clusters. The variance of the extreme SAT among the warm events in each cluster is much smaller than that in the cold extreme clusters (Fig. 15b).

Comparing the cluster regimes of the cold extremes to those of the warm extremes, they all show an intensified pressure anomaly over Europe, but the patterns over the Atlantic are different. The diverse locations of the circulations over the Atlantic distinguish each cluster from others, causing differences in the intensity of extremes, the stability of the circulation, and the probability of extreme occurrences. Most regimes exhibit anomalous flow and thermal advection in a northeast–southwest direction. The NAO phase determines the preferred occurrence of the blocking or positive NAO events, causing the asymmetry in location between the cold and warm extremes.

b. Asymmetry in intensity

The asymmetry in intensity can manifest in temporal evolution and the departure of the extreme SAT value from the mean. To examine the evolution time scale of the local cold and warm extreme events and the relationship between the cold/warm extremes and the winter mean SAT, the PDFs of the maximum departure of the cold (warm) extreme SAT from the 31-day mean, and the continuous days of decreasing (increasing) SAT during the developing period are calculated for all the selected cold (warm) extreme events at location 1 (location 2).

The maximum departure refers to the absolute value of the difference between the minimum (maximum) SAT of an individual cold (warm) extreme event and the 31-day average of the SAT spanning from lag 15 to lag 15 days. The maximum departure may be considered as the amplitude of the cold (warm) extreme. The continuous decreasing (increasing) days measure the duration for which SAT monotonically decreases (increases) before it reaches its minimum (maximum) (lag 0). This may be considered as the half-duration length of the cold (warm) extreme event, representing the time scale...
in which the extreme event is influenced by the blocking (positive NAO) and the transient process on the cold (warm) extreme event.

Figure 16a shows that the minimum SAT of the cold extreme events deviates significantly farther from the mean SAT than the warm extremes. The PDF of the half length of the cold extreme events peaks at the time scale of about 4–5 days; while it shows two peaks for the warm extreme events (Fig. 16b), the major peak is about 2–3 days, and the minor one is about one week. The 4–5-day half duration of cold events (Fig. 16b) indicates the combined effects of the transient and the submonthly processes, with the submonthly process being dominant (see also Figs. 5a, b and Fig. 9a). The short half duration and weak amplitude of the warm extremes are due to a simple increase in the monthly mean value (Fig. 16b).

c. Asymmetry in temperature variance

The local SAT variation is determined by velocity ($u, v$, and $\omega$) and the gradient of potential temperature ($\partial \theta / \partial x$, $\partial \theta / \partial y$, and $\partial \theta / \partial p$). The horizontal SAT gradient plays a role in the warm and cold extreme events. The correlation coefficient between the horizontal SAT gradient and the cold extremes is large over most of the
European continent, especially over northwest Europe (Fig. 17a). This can be explained by the strong cold air advection by the eastward-shifted blocking circulation. The northerly anomalous flow and cold advection increase the SAT gradient, but the southerly flow and warm advection act oppositely, decreasing the SAT gradient (Fig. 17b). The accumulated effects of the cold and warm advection result in the significant change of the background SAT gradient. Furthermore, 850-hPa transient eddies are also active (inactive) (Fig. 8) over a major part of Europe in the cold (warm) extreme winter. Thus, the combined effects of the increased SAT gradient, the presence of the blocking circulation, and energetic transient eddies all act to increase the SAT variance from submonthly to transient synoptic time scales for cold extreme winters. But the situation is almost opposite for warm extreme winters. Additionally, the cluster analysis indicates that the variance of extreme SAT is large (small) within each cold (warm) extreme cluster, consistent with the notion that the warm extremes are due to the increase of the mean SAT rather than the SAT variance. As a result, the asymmetric deviations of the cold and warm extreme SAT from winter mean SAT are due to the different effect of the blocking and the positive NAO on the background mean SAT.

6. Summary and discussion

The leading EOFs of the cold and warm extremes show two main action centers over Baffin Bay and Europe with opposite signs, resembling the NAO-induced patterns of SAT variability. The frequency of SAT extreme occurrences over Europe is correlated with the NAO for the cold (warm) extremes; while the occurrence of warm extremes is mainly affected by the NAO-related changes in seasonal mean SAT, the cold extremes are also related to both the decreased seasonal mean temperature and the increased SAT subseasonal variance.

The advection of submonthly temperature variation by the persistent blocking (positive NAO) circulation contributes to the development of cold (warm) extreme events (Fig. 6). The anomalous advection peaks 1–2 days prior to the peak of an extreme event. The advection of transient (submonthly) temperature variation by submonthly (transient) varying flow is also important, contributing at lag −1 day and lag 0 day of the extreme event. The advection of transient temperature perturbation by the submonthly flow is the most important cause of the decay of warm extremes. Both the double transient term (the advection of transient temperature perturbation by transient flow) and the cross terms involving the mean flow/temperature and the submonthly (transient) flow/temperature variation are almost negligible. Thus, the life cycles of cold and warm extreme events are controlled by the submonthly evolution of the blocking circulation/positive NAO event and the transient eddies steered by the flow patterns.

The cold and warm extremes are asymmetric in spatial distribution, with cold extremes mainly over northwest Europe and warm extremes over northeast Europe. This is controlled mainly by the phases of NAO. By modulates the occurrence of the blocking and positive NAO event, the warm and cold extremes differ in location as they are displaced downstream of the anomalous meridional flow.

The circulation fields leading to cold extreme event are clustered into three regimes: the western Atlantic blocking, the Scandinavian blocking, and the eastern Atlantic blocking. The 500-hPa height fields leading to the warm extreme events are clustered into two regimes: the zonal wave train-like and meridional positive NAO patterns, with the meridional pattern being the dominant regime accounting for the majority of the warm extreme events.
All the clustered regimes show a pressure anomaly over the European continent for both cold and warm extremes; but the patterns over the Atlantic are different. The diverse locations of the circulations over the Atlantic distinguish each cluster from the others, causing differences in the intensity of extremes, the stability of the circulation, and the probability of extreme occurrences. Most regimes exhibit the anomalous winds in a northeast–southwest direction.

The cold advection by the anomalous northerly flow results in the decreasing SAT and increasing background SAT gradient, thereby intensifying the SAT variance in northwest Europe. The occurrence of the eastward-shifted positive NAO pattern induces the southwesterly flow that advects warm air to northeast Europe, causing warming and decreasing the background SAT gradient. The decreased SAT gradient weakens the SAT variance. Thus, the asymmetry between the cold and warm extremes is also manifested by the difference in the deviations from the monthly mean value. Cold extreme events feature large departures from the mean value and are associated with increased SAT variance. Warm extremes are weaker in magnitude and associated primarily with changes in seasonal mean, with little contribution from SAT variance.

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