LETTER

Summer Russian heat waves and their links to Greenland's ice melt and sea surface temperature anomalies over the North Atlantic and the Barents–Kara Seas

Hejing Wang and Dehai Luo

1 Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People's Republic of China, 100029
2 University of Chinese Academy of Sciences, Beijing, People's Republic of China

E-mail: ldh@mail.iap.ac.cn

Keywords: Russian heat waves, Rossby wave train, SST anomaly, Greenland blocking, North Atlantic blocking, North Atlantic Oscillation, Greenland ice melting

Supplementary material for this article is available online

Abstract

In this paper, we examine what leads to the onset of summer Russian heat waves. The reanalysis data show that summer heat waves over west Russia have two types of spatial patterns: mid-latitude heat waves related to mid-latitude Ural blocking (UB) events occurring at the longitudes of 30°–70°E and at the midlatitudes of 40°–60°N, and high-latitude heat waves related to high-latitude UB events occurring at the longitudes of 50°–100°E and at the high latitudes of 50°–75°N. It is found that the two types of UB events have different dynamic origins. While the high-latitude UB results from the propagation of Rossby wave trains due to the decay of Greenland blocking, mainly related to strong ice melting over Greenland’s land, the mid-latitude UB originates from the decay of North Atlantic blocking mainly related to positive extratropical North Atlantic sea surface temperature (SST) anomalies associated with a positive Atlantic Multidecadal Oscillation (AMO+). We demonstrate that the sign of the SST anomaly over the Barents–Kara Sea (BKS) influences the UB in position and strength. In particular, the impact of a positive BKS SST anomaly on the high-latitude UB is strong, which leads to a high-latitude UB through an anticyclonic anomaly over the BKS and its combination with the UB anticyclone resulting from the decay of Greenland blocking. By comparison, the effect of a BKS SST anomaly on the mid-latitude UB is relatively weak. It is further revealed that a strong Greenland ice melt, a positive BKS SST anomaly and a strong negative North Atlantic Oscillation are the precursors of high-latitude UB, whereas an extratropical AMO+ SST anomaly and a negative BKS SST anomaly are the precursors of mid-latitude UB.

1. Introduction

In recent decades, the global surface temperature has shown a pronounced increasing trend, which is often referred to as global warming. Along with global warming, summer heat waves have occurred frequently in the Northern Hemisphere (NH), which have exhibited an obvious positive trend (Yan et al 2002; Alexander et al 2006, Zhang et al 2011, Weaver et al 2014). The best-known examples of the NH heat waves are the summer heat waves that occurred over Europe in 2003 and over western Russia in 2010 (Dole et al 2011, Schneidereit et al 2012, Johnson et al 2018). These frequent intense summer heat waves have seriously affected the natural ecology, environment and agriculture production and the functioning of human society, even taking people’s lives. For example, the European heat wave in the summer of 2003 caused more than 70 000 deaths, whereas the Russian heat wave the summer of 2010 caused 55 000 deaths and $1.5 billion in economic losses (Robine et al 2008, Coumou and Rahmstorf 2012). Thus, the causes and mechanisms of the generation and variability of these summer heat waves have been an important research topic and have attracted great deal of scientific attention from around the world (Tett et al...
1999, Black et al 2004, Vautard et al 2007, Johnson et al 2018).

It has been widely recognized that NH summer heat waves are mainly affected by both external forces and internal variability (Tett et al 1999, Stott et al 2000, 2004, Schär et al 2004, Meehl and Tebaldi 2004, Sutton and Hodson 2005, Trigo et al 2005, Baldi et al 2006, Della-Marta et al 2007; Li et al 2018), while they show distinct regional characteristics in terms of intensity and duration (Fischer and Schär 2010). Stott et al (2004) and Klein Tank et al (2005) noted that
anthropogenic influence played an important role in the 2003 European heat wave. Although model simulation studies have revealed that the NH’s summer heat waves will become stronger, longer-lived and more frequent in future warming decades (Meehl and Tebaldi 2004, Barriopedro et al 2011, Lau and Nath 2014), internal atmospheric variability has also been shown to play an important role in summer heat waves (Dole et al 2011, Treberth and Fasullo 2012).

In particular, individual summer heat wave events are mainly caused by atmospheric blocking anticyclones within the heat wave region (Dole et al 2011, Pfahl and Wernli 2012, Schaller et al 2018, Sousa et al 2018, Liu et al 2020) that are related to Rossby wave trains propagating to the European continent from the North Atlantic (Cassou et al 2005, Ghosh et al 2017, 2019). These summer heat waves are also linked to a lack of Mediterranean winter and spring precipitation (Vautard et al 2007) and soil-moisture temperature and precipitation feedback (Zaitchik et al 2006; Seneviatne et al 2006). For example, the Russian heat wave in the summer of 2010 was found to be mainly due to an intense and long-lived blocking anticyclone over west Russia (Dole et al 2011, Schneideret et al 2012) and associated with a Rossby wave train with an anticyclonic anomaly over the Ural region due to strong convection in the tropical Atlantic (Trenberth and Fasullo 2012). Unfortunately, the factors that led to the change of the region where the Russian heat waves occur were not investigated in their studies.

Some studies have attributed the long-term variability of NH summer heat waves, especially those over Europe and west Russia, to the Atlantic Multidecadal Oscillation (AMO) (Sutton and Hodson 2005, Johnson et al 2018), and winter North Atlantic sea surface temperature (SST) anomalies (Colman 1997, Cassou et al 2005). The North Atlantic SST has a great influence on heat waves in the NH especially those in Europe (Kamae et al 2014, Dong et al 2017, Mecking et al 2019, Ehsan et al 2020), which also plays an important role in the prediction of heat waves on decadal time scales (Ghosh et al 2017, Borchert et al 2019). However, the previous studies did not examine what types of atmospheric circulation and SST pattern favor high-latitude and mid-latitude heat waves and whether the North Atlantic SST anomaly is also important for the occurrence of high-latitude Russian heat waves.

In this paper, our attention is mainly focused on examining the following questions: (1) what are the atmospheric circulation patterns that favor summer Russian heat waves in different regions? (2) Are mid-latitude and high-latitude heat waves related to summer SST anomalies over the North Atlantic and the Arctic? The investigation of these issues can deepen our understanding of the dynamic causes of summer Russian heat waves in different locations.

2. Data and method

We used six-hourly ECMWF Re-Analysis interim (ERA-interim) data, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), from the summer (from June to August, JJA hereafter) from June 1979 to August 2017 (1979–2017) with a horizontal resolution of $1^\circ \times 1^\circ$ grid points, taken from the European Center for Medium-Range Weather Forecasts (datasets/data/interim-full-daily/) (Dee et al 2011). The daily data set includes the surface air temperatures (SAT) (air temperature at 2 m above the Earth’s surface), 500hPa geopotential heights (Z500), SST and 500 hPa horizontal winds (U500 & V500). An anomaly in a variable is defined as its deviation from the climatological mean for each calendar day at each grid point. We also used the monthly mean SST (HadISST) dataset on a $1^\circ \times 1^\circ$ grid for the period from June 1979 to August 2017 from the Hadley center (.gov.uk/hadobs/hadisst/data) (Rayner et al 2003) to calculate the summer SST anomalies over the North Atlantic and the Arctic. To see whether the SST anomaly depends on the evolution of Ural blocking (UB), we use the daily SST data from the ERA interim reanalysis data to calculate the variation in the daily SST anomalies.

Here, the daily meltwater production in the unit of mm water equivalent (mmWE) over Greenland’s land is used to describe the daily variation in Greenland’s ice sheet (GrIS) that reflects Greenland’s ice melt (GIM), which is taken from the MARV3.11 output data, provided by the GrIS reanalysis data based on the Modèle Atmosphérique Régional version 3.5.2 regional climate model for the GrIS (Fettweis et al 2017). The daily North Atlantic Oscillation (NAO) index we use here is taken from the NOAA Climate Prediction Center (/pna/nao.shtml), whereas the monthly AMO index used to calculate the summer (JJA-mean) AMO index is available from the NOAA Physical Sciences Laboratory (https://psl.noaa.gov/data/timeseries/AMO) (Enfield et al 2001).

For each grid point, we define any day when the daily maximum temperature ($T_{\text{max}}$, air temperature at 1200 UTC) exceeds the 90th percentile of the daily $T_{\text{max}}$ series to be a heat wave day. A heat wave event is defined as one that persists for three consecutive days or more. For each year, the summer heat wave
frequency (HWF) is defined as the sum of all heat wave days of heat wave events in summer. In this paper, empirical orthogonal function (EOF) analysis is used to identify the spatial patterns of the HWF over west Russia to establish a link between the HWF modes and atmospheric circulation, SST and ice variables by calculating their correlation. Although the second and third EOF (EOF2 and EOF3) modes of the HWF are not well separated during 1979–2017, the first and second EOF (EOF1 and EOF2) modes can be crudely separated. Thus, we only consider the EOF1 and EOF2 modes of the HWF in this study. Of course, a longer data sample size is needed to extract more separated spatial modes of the HWF over West Russia. The results obtained in this paper can also be validated using singular value decomposition (SVD) (supplementary material available online at stacks.iop.org/ERL/15/114048/mmedia)).

To identify UB events (large-scale, long-lived anticyclones over the Ural Mountains) in the summer (Dole et al 2011), we use the one-dimensional blocking index of Tibaldi and Molteni (1990, TM) based on the reversal of the meridional Z500 gradient in the blocking region. The meridional gradients of the Z500 field are GHGN = \((Z500(\phi N) - Z500(\phi S))/\phi S - \phi N\) and GHGS = \((Z500(\phi N) - Z500(\phi S))/\phi S - \phi N\) at three given reference latitudes: \(\phi N = 80^\circ N + \Delta\), \(\phi S = 60^\circ N + \Delta\), \(\phi N = 40^\circ N + \Delta\) for \(\Delta = -4^\circ, 0^\circ, 4^\circ\), respectively. Following Tibaldi and Molteni (1990), a 5-day moving average of the daily Z500 anomaly fields is conducted to filter out synoptic-scale or high-frequency disturbances to reflect large-scale features of the blocking flow before the TM index is applied, which can improve the identification of blocking events and reduce the number of cases where synoptic-scale high pressure systems are identified as blocking. A blocking event is defined to have taken place in the Ural Mountains and its adjacent regions if both of the conditions GHGS > 0 and GHGN < −10 gpm (deg lat)\(^{-1}\) are satisfied and persist over at least three consecutive days for at least one of the three values of \(\Delta\). The methods used in this paper, namely the Monte-Carlo test, Mann-Kendall testing, the F-test and the two-sided student t-test can be found in Wilks (2011). Moreover, the horizontal wave activity flux (WAF) of Takaya and Takaya (2001) (their equation (32)) is calculated to represent the horizontal propagation of Rossby wave trains associated with UB events.

3. Results

To detect the region where summer heat waves occur over Eurasia, it is useful to calculate the linear trend of the HWF for the years 1990–2013 and 1979–2017. It is found that the linear trend of the HWF from 1990–2013 (figure 1(a)) shows a spatial pattern similar to that of 1979–2017 and a more pronounced upward trend from 1990–2013 than for 1979–2017 (figure S1 in the supplementary material). The most pronounced increased trend of the summer HWF from 1990–2013 takes place mainly over west Russia (40°–70°N, 25°–75°E) and its south side. The time series of JJA-mean HWFs averaged for west Russia (40°–70°N, 25°–75°E) is shown in figure 1(b). It can be seen that the HWF shows a linear upward trend with an increase of about 3.1 d per decade from 1990–2013 (figure 1(b)). This suggests that global warming has made a large contribution to an increased trend of the HWF frequency over west Russia. This result can also be seen in the NCEP-NCAR reanalysis data (not shown). The result that the long-term upward trend of the HWF in the NH is mainly related to global warming has been noted by many previous studies (e.g. Stott et al 2004). Thus, in this paper our major purpose is not to examine the cause of the upward trend of the HWF, but instead to examine the role of internal variability in the HWF change.

3.1. Links to SST anomalies and Greenland’s ice melt

In this paper, because our purpose is to understand what leads to the internal variability of the summer heat wave over west Russia and its regional change, we need to examine the spatial structure of the HWF over west Russia. For this reason, all the fields we present below are linearly detrended and the EOF analysis of the HWF over west Russia is performed. We show the EOF1 and EOF2 modes of the linearly detrended summer HWF anomalies with a latitude weighting of grid data over west Russia (40°–70°N, 25°–75°E) for 1979–2017 and the time series of their corresponding normalized principal components (PC1 and PC2) in figures 1(c)–(f). It is found that the heat wave occurs over the west Russian midlatitudes mainly to the west of 50°E and in the mid-latitudes (40°–60°N), with a central latitude of about 50°N for the EOF1 mode (figure 1(c)), but mainly to the east of 50°E and at high latitudes (50°–75°N) with a central latitude of 65°N for the EOF2 mode (figure 1(d)). Thus, the Russian heat wave pattern associated with the EOF1 (EOF2) mode may be referred to as the mid-latitude (high-latitude) Russian heat wave to represent the Russian heat waves in different regions. The two heat wave modes are also not influenced by the latitude weighting of the grid data (not shown). Moreover, we see that the 2010 Russian heat wave, investigated by previous studies (e.g. Dole et al 2011, Schneidereit et al 2012, Trenberth and Fasullo 2012), belongs to the group of mid-latitude Russian heat waves because the PC1 time series has a very strong peak in 2010 (figure 1(e)). However, the high-latitude HWF increased significantly during 2010–2017 (figure 1(f)), thus implying that the Russian heat waves have tended to take place at higher latitudes after 2010.

To examine the types of atmospheric circulation patterns that are linked to the mid-latitude and high-latitude Russian heat waves, we first show the JJA-mean Z500 and SAT anomalies regressed
onto the PC1 and PC2 time series of the HWF in figures 2(a) and (b). It is found that the mid-latitude Russian heat waves correspond to summer midlatitude Ural anticyclones confined to the mid-latitudes (40°–60°N) and at the longitudes of 30°–70°E with anticyclonic centers at 47°E and 55°N (figure 2(a)), whereas the high-latitude Russian heat waves are associated with summer high-latitude Ural anticyclones confined to the high latitudes (50°–75°N) and at the longitudes of 50°–100°E with anticyclonic centers at 67°E and 64°N (figure 2(b)). We also note that the mid-latitude Ural anticyclones seem to result from the propagation of wave trains from the North Atlantic to Eurasia along the south of Greenland (figure 2(a)). In contrast, the high-latitude Ural anticyclones originate from the propagation of high-latitude wave trains from Greenland to Eurasia (figure 2(b)). As revealed by the daily composites (figure 6) presented below, the positive JJA-mean Z500 anomalies over Greenland (the south of Greenland) correspond to Greenland blocking (North Atlantic blocking). Thus, the generation of the summer mid-latitude (high-latitude) Ural anticyclones is likely to be associated with the appearance of summer North Atlantic blocking (Greenland blocking).

Because North Atlantic blocking (Greenland blocking) is often coupled with North Atlantic SST (GrIS) anomalies (Ballinger et al. 2019, Kwon et al. 2020), it is useful to examine the types of summer SST (GrIS) anomaly that correspond to North Atlantic blocking (Greenland blocking). We show the JJA-mean SST anomalies from the HadISST dataset and meltwater production over Greenland (referred to as the Greenland Ice Melts, hereafter) regressed onto the PC1 and PC2 time series of the summer HWF in figures 2(c)–(f). It can be seen that the mid-latitude Russian heat waves (HWF EOF1) correspond to strong positive SST anomalies over the North Atlantic mid-latitudes (40°–60°N) mainly in the south of Greenland and a negative SST anomalies over the Barents–Kara Seas (BKS, 35°–70°E, 65°–80°N) (figure 2(c)). Compared to other regions, relatively strong positive SST anomalies mainly appear at high latitudes in
Figure 2. (a) and (b) JJA-mean Z500 (contours; contour interval = 5 gpm) and SAT (color shading with the 95% confidence level) anomalies, (c) and (d) SST (color shading) anomaly and (e) and (f) Greenland Ice Melt (meltwater production over Greenland; unit: mmWE where WE denotes water equivalent) regressed onto the HWF PC1 and PC2 time series over western Russia (40°–70° N, 25°–75° E) with latitude weighting of the grid data for 1979–2017. In panels c-f, the dot represents the region above the 95% confidence level for a $F$-test. The thick black arrow denotes the wave propagation direction, which is the same as below.

The North Atlantic, especially over Baffin Bay, Davis Strait, the Labrador Sea and the east of the southern tip of Greenland (BDL, hereafter) and over BKS during the high-latitude Russian heat waves (HWF EOF2) (figure 2(d)). We also find that the Greenland Ice Melts, especially on the northeast side of Greenland’s landmass, are stronger during the high-latitude heat waves (figure 2(f)) than the mid-latitude heat waves (figure 2(e)). These results lead us to conclude that the midlatitude Russian heat waves are associated with positive North Atlantic midlatitude SST anomalies and negative SST anomalies over BKS, whereas the high-latitude Russian heat waves are most likely linked to intense Greenland Ice Melts and positive SST anomalies over BDL and BKS. This results are not significantly changed by changes in the domain size of the EOF analysis. Our further calculation indicates that the results for a large domain (40°–70° N, 25°–75° E). It is also noted that the EOF1 and EOF2 modes of the JJA-mean HWF are approximately separated during 1979–2017, even though they slightly depend on the size of the EOF domain. The two heat wave modes can still be found even when SVD is used (figures S4–S5 in the supplementary material).

Furthermore, we can see that the positive North Atlantic SST pattern in figure 2(c) resembles the extratropical SST anomalies of the positive AMO+ or the positive phase of the Atlantic multidecadal variability (AMV) (Ghosh et al 2019, their figure 1(b)). Although Ghosh et al (2019) investigated the roles of the positive and negative AMV SST anomalies in the central to eastern European summer climate, they did not examine the role of the extratropical AMO+ SST anomalies in Russian heat waves. As opposed to their study, in this paper we mainly investigate the conditions under which mid-latitude (high-latitude) Russian heat waves can occur. It is shown that the
extratropical North Atlantic SST anomalies of the AMO+ mainly influence the mid-latitude Russian heat wave, whereas the high-latitude Russian heat waves are mainly linked to intense Greenland ice melts.

To demonstrate whether the UBs that result from the propagation of upstream wave trains are related to changes in SST anomalies and Greenland Ice Melts, it is useful to examine the daily evolution of the composite UBs associated with mid-latitude (high-latitude) Russian heat waves. To investigate this problem, any normalized PC1 (PC2) time series with at least a 0.5 standard deviation (STD) in the summer HWF EOF1 (EOF2) mode is defined as a strong mid-latitude (high-latitude) heat wave, which is the case for 1981, 1988, 1995, 1998, 1999, 2006 and 2010 (1981, 1982, 1988, 1989, 1990, 1991, 1998, 2003, 2004, 2007, 2012 and 2016). Using the TM index, we find that there are 24 and 35 UB events in the Ural regions 30°–90°E and 40°–100°E for strong mid-latitude (7 cases) and high-latitude (12 cases) heat wave summers, which correspond to 3.42 and 2.92 UB events per summer, respectively. Thus, UB events are relatively more frequent in strong mid-latitude heat wave summers than in strong high-latitude heat wave summers.

We show the time-mean composite daily Z500 and SAT anomalies averaged from lag –10 to 10 d (lag 0 denotes the peak day of blocking) in figure 3 for the strong mid-latitude and high-latitude heat wave summers. It is found that the positive center of the time-mean composite Z500 anomalies of the UB events is located near 45°E and 55°N for the mid-latitude heat waves (figure 3(a)), but near 70°E and 65°N for the high-latitude heat waves (figure 3(b)). Thus, it is reasonable that the UB events associated with the mid-latitude (high-latitude) heat waves are referred to as mid-latitude (high-latitude) UB events hereafter. Because the time-mean position of the composite UB anticyclones is consistent with the positive center of the regressed JJA-mean Z500 anomalies against the HWF PC1 (PC2) time series, individual mid-latitude (high-latitude) UB events are the main contributors to the summer-mean mid-latitude (high-latitude) Ural anticyclones, as seen from figures 2(a) and (b). This indicates that the maintenance of mid-latitude (high-latitude) UB events is responsible for the occurrence of strong summer mid-latitude (high-latitude) Russian heat waves. The calculation using the time-mean WAF vector of Takaya and Takaya (2001) shows that mid-latitude (high-latitude) UBs seem to originate from the propagation of upstream wave trains (blue arrows in figures 3(a) and (b)). Below, we will present a daily composite WAF vector associated with UB events, to demonstrate that the occurrences of the mid-latitude (high-latitude) UB events result from decays of North Atlantic blocking (Greenland blocking).

3.2. Impacts of Greenland ice melts and SST anomalies in different regions and their cooperative effects

As noted above, the mid-latitude and high-latitude Russian heat waves can correspond to different summer North Atlantic SST, Arctic SST and GrIS anomaly patterns. In this subsection, we further evaluate which of the SST and GrIS anomalies is important for the mid-latitude (high-latitude) UBs. We show the time series of normalized JJA-mean SST anomalies averaged over the North Atlantic (40°–60°N,25°–75°W), BKS (65°–80°N, 35°–70°E), BDL (60°–75°N, 20°–75°W) and JIA-mean Greenland Ice Melts in figures 4(a)–d. Their correlation coefficients with the HWF PC1 and PC2 time series and the correlation coefficients of the summer AMO indexes (Fig. S6 in the supplementary material) with the HWF PC1 and PC2 time series are presented in table 1. The regressed JJA-mean Z500 and SAT anomalies onto the normalized time series of domain-averaged SST anomalies and Greenland Ice Melts are shown in figures 4(e)–h. It can be observed that the mid-latitude (high-latitude) Ural anticyclones are mainly related to the positive extratropical North Atlantic SST anomalies (Greenland ice melting) through the generation of North Atlantic blocking (Greenland blocking) (figures 4(e), h).

We also see that the center of the mid-latitude (high-latitude) Ural anticyclones of the JIA-mean Z500 regressed into the North Atlantic SST anomaly (Greenland Ice Melt) time series is located near 58°E and 56°N (62°E and 58°N) under the condition that the role of the BKS SST anomalies is excluded. The Z500 anticyclonic (cycloic) anomalies in response to the positive (negative) BKS SST anomalies are centered near 64°E and 69°N. Clearly, when the BKS SST anomalies are not considered, the positions of the mid-latitude (high-latitude) Ural anticyclones obtained are very different, compared to the results in figures 2(a)–(b). Based on this, we conclude that the BKS SST anomalies are also important for the regional change of UBs, because positive (negative) BKS SST anomalies can correspond to positive (negative) Z500 anomalies over the BKS (figure 4(f)). As noted below, the positions of the positive JJA-mean Z500 anomalies obtained for mid-latitude (high-latitude) Russian heat waves become more consistent with those in figures 2(a)–(b), when both the extratropical North Atlantic SST anomalies (Greenland Ice Melts) and the BKS SST anomalies are considered. When a positive BDL SST anomaly corresponds to a positive Z500 anomaly over Greenland or a Greenland anticyclone (figure 4(g)), the Ural anticyclone resulting from this Greenland anticyclone appears to be rather weak in this case. This suggests that the role of a BDL SST anomaly is secondary to the occurrence of a high-
Figure 3. Time-mean composite daily Z500 (contours; CI = 10 gpm) and SAT (color shading, unit: K) anomalies averaged from lag −10 to 10 d during the blocking life cycle of (a) 24 mid-latitude UB events in seven strong mid-latitude heat wave summers and (b) 35 high-latitude UB events in 12 strong high-latitude heat wave summers, where lag 0 denotes the peak day of the UB. The color shading denotes the region above the 95% confidence level for a two-sided student t-test. The blue arrow represents the wave activity flux vector.

Figure 4. (a)–(d) Time series of JJA-mean SST anomalies averaged for the North Atlantic (NA; 40° - 60°N, 25° - 75°W), the BKS (65° - 80°N, 35° - 70°E), BDL (60° - 75°N, 20° - 75°W) and the JJA-mean meltwater production anomalies (as the Greenland Ice Melts) during 1979–2017. (e)–(h) Detrended JJA-mean Z500 (contours; CI = 5 gpm) and SAT (color shading) anomalies regressed onto domain-averaged SST time series for (e) the NA, (f) the BKS, (g) BDL and (h) domain-averaged Greenland Ice Melts during 1979–2017. The color shading in panels e–h denotes the region above the 95% confidence level for an F-test.
latitude UB, compared to the role of a Greenland Ice Melt.

The correlation calculation (table 1) shows that the mid-latitude Russian heat waves, as denoted by the HWF EOF1 mode, have significant positive correlations of 0.40, 0.41 and 0.38 ($p < 0.05$) with the AMO indexes, the midlatitude North Atlantic SSTs and the BDL SSTs, although the HWF PC1 exhibits a modest significant positive (negative) correlation of $-0.28$ ($0.3$) ($p < 0.1$) with the BKS SST (Greenland Ice Melts). This hints that the mid-latitude Russian heat waves are more closely related to the positive extratropical North Atlantic SST anomalies, BDL SSTs and AMO$^+$. However, we find that while the HWF PC1 has a significant positive correlation with the BDL SST anomalies, the role of the BDL SST anomalies in the mid-latitude heat waves (figure 4(g)) is relatively weak compared to that of the extratropical North Atlantic SST anomalies (figure 4(e)). Although the positive extratropical North Atlantic SST anomalies resemble the AMO$^+$ SST patterns, our correlation calculation further reveals that positive extratropical North Atlantic SST anomalies (for an example, see figure 2(c)) are likely to be due to the AMO$^+$, because their positive correlation coefficients with the summer AMO indexes (Fig. S6) were able to reach 0.50 ($p < 0.01$) during 1979–2017. The positive BDL SST anomalies are also likely to be part of the AMO$^+$, because they have a positive correlation of 0.35 ($p < 0.05$), although they are relatively weak compared to the extratropical anomalies of the AMO$^+$ SST. The North Atlantic midlatitude SST anomalies will be referred to as the extratropical AMO$^+$ SST anomalies hereafter.

We can see from table 1 that the high-latitude Russian heat waves, as denoted by the HWF EOF2 mode, have a large positive correlation of 0.45 ($p < 0.01$) with the Greenland Ice Melts and a modest significant correlation of 0.30 ($p < 0.1$) with the BKS SST anomalies, but no significant correlations with the AMO indexes, North Atlantic SST anomalies and BDL SST anomalies. Although the BKS SST anomalies show a significant negative correlation of −0.37 ($p < 0.05$) with the BDL SST anomalies, they have an insignificant negative correlation of $-0.13$ ($-0.21$) with the extratropical AMO$^+$ SST (Greenland Ice Melt) anomalies. We further find that the Greenland Ice Melts have a large positive correlation of 0.68 ($p < 0.01$) with the BDL SST anomalies, though the BDL SSTs show a modest significant positive correlation of 0.29 ($p < 0.1$) with the extratropical AMO$^+$ SST anomalies. Thus, the Greenland Ice Melts are more likely due to the positive BDL SST anomalies. It is possible that the BDL SST anomalies play an indirect role in the variability of Russian heat waves via the GrIS or Greenland Ice Melt changes. This leads us to infer that high-latitude Russian heat waves are mainly related to Greenland Ice Melts and BKS SST anomalies. The new results are different from the previous findings of Trenberth and Fasullo (2012), who noted that tropical North Atlantic SST anomalies can have a large contribution to Russian heat waves in 2010. However, here we find that Greenland Ice Melts play a large role in high-latitude Russian heat waves. The numerical experiments of Ghosh et al (2019) also indicated that mid-latitude Urals anticyclones mainly arise from the forcing of positive extratropical North Atlantic SST anomalies rather than from the forcing of tropical North Atlantic SST anomalies as found in Trenberth and Fasullo (2012) for the 2010 summer Russian heat wave. As opposed to the previous studies, we further find that the Greenland Ice Melts and the BKS SST anomalies are also important for the positions and strengths of summer Russian heat waves.

Because the Greenland ice melt (GIM) or extratropical North Atlantic SST anomaly (SST$_{NA}$) has an insignificant correlation with the BKS SST anomaly (SST$_{BKS}$), one can use a binary linear regression model to estimate the combined contribution of SST$_{NA}$ (GIM) with SST$_{BKS}$ to the mid-latitude (high-latitude) Russian heat waves by reconstructing the HWF PC1 (PC2) time series. Using $PC_1 = \alpha_1$SST$_{NA} + \alpha_2$SST$_{BKS} \times (-1.0)$, we show the reconstructed HWF PC1 time series in figure 5(a), where $\alpha_1 = 0.38$ ($\alpha_2 = 0.23$) is the regression coefficient of (SST$_{BKS}$) onto the PC1 time series of the HWF EOF1 mode. The reconstructed HWF PC2 time series from $PC_2 = \alpha_1$GIM + $\alpha_2$SST$_{BKS}$ is also shown in figure 5(b), where $\alpha_1 = 0.53$ ($\alpha_2 = 0.42$) is the regression coefficient of GIM (SST$_{BKS}$) onto the PC2 time series of the HWF EOF2 mode. As shown in table 1, the reconstructed HWF PC1 (PC2) time series has a significant positive correlation of 0.47 (0.60) ($p < 0.01$) with the HWF PC1 (PC2) time series in figures 1(d)–(f). Clearly, the inclusion of SST$_{BKS}$ can increase the positive correlation of the extratropical AMO$^+$ SST anomalies (Greenland Ice Melts) with mid-latitude (high-latitude) Russian heat waves. The JJA-mean Z500 and SAT anomalies regressed onto

| Table 1. Correlation coefficients of the HWF PC1 and PC2 time series over west Russia with the JJA-mean AMO, domain-averaged JJA-mean SST anomalies over the North Atlantic (NA), the BKS and BDL; domain-averaged Greenland Ice Melts (meltwater production over Greenland’s landmass) and the reconstructed HWF PC1 (PC2) time series from the domain-averaged JJA-mean North Atlantic SST anomalies and the BKS SST anomalies (during 1979–2017). The two-asterisked (one-asterisked) numbers represent the 95% (90%) confidence level for a student t-test. |

| HWF PC SST, GIM and AMO index | HWF PC1 | HWF PC2 |
|--------------------------------|---------|---------|
| AMO                            | 0.40**  | 0.24    |
| North Atlantic SST             | 0.41**  | 0.03    |
| BKS SST                        | $-0.28^*$ | 0.30*    |
| BDL SST                        | 0.38**  | 0.20    |
| Greenland Ice Melt             | 0.30*   | 0.45**  |
| NA SST + BKS SST $\times (-1)$ | 0.47**  | $-0.12^*$ |
| Greenland Ice Melt + BKS SST    | 0.07    | 0.60**  |
the reconstructed HWF PC1 and PC2 time series (figures 5(c) and (d)) further reveal that the center of the Ural anticyclone in the regressed JJA-mean Z500 anomaly field against the reconstructed HWF PC1 (PC2) time series in figures 5(a) and (b) is located near 53°E and 55°N (64°E and 65°N), closer to that in figure 2(a) and (b) when the negative (positive) BKS SST anomalies are considered, though there is a small difference with those in figures 2(a) and (b). Thus, the presence of mid-latitude (high-latitude) UBs is more likely due to the combined effects of the extratropical AMO+ SST anomalies and the negative BKS SST anomalies (the Greenland Ice Melts and the positive BKS SST anomalies), though they stem from the decay of North Atlantic blocking (Greenland blocking) and the propagation of associated wave trains. While the extratropical AMO+ SST anomalies (Greenland Ice Melts) play a major role, the negative (positive) anomalies of the BKS SST seem to influence the location and strength of UBs. A comparison between figures 4 and 5 indicates that negative (positive) BKS SST anomalies tend to cause southwestward-(northeastward-) displaced UBs with weak (strong) intensities through the presence of negative (positive) Z500 anomalies over the BKS. The combination of an extratropical AMO+ SST anomaly and a negative BKS SST anomaly (a Greenland Ice Melt and a positive BKS SST anomaly) can make an UB anticyclone have an anticyclonic center closer to that of a mid-latitude (high-latitude) UB associated with the HWF EOF1 (EOF2) mode (figures 2(a) and (b)) than the role of an extratropical AMO+ SST anomaly (Greenland Ice Melt) without the effect of a BKS SST anomaly. Of course, other factors play a role in the locations where summer UB anticyclones occur, which deserve further investigation.

We conclude from the above results that extratropical AMO+ SST anomalies over the North Atlantic and negative BKS SST anomalies can combine to cause mid-latitude Russian heat waves over west Russia through the generation of mid-latitude UBs, even though the North Atlantic SST anomalies play a bigger role than the negative BKS SST anomalies. In contrast, the Greenland Ice Melts and positive BKS SST anomalies combine to result in high-latitude Russian heat waves via the generation of high-latitude UBs. Below, we create a daily composite to reveal the physical mechanism of UB generation and to demonstrate that the propagation of Rossby wave trains associated with the evolution of North Atlantic blocking (Greenland blocking) leads to mid-latitude (high-latitude) UBs.

3.3. Propagation of wave trains associated with the decay of North Atlantic blocking and Greenland blocking and the North Atlantic precursors of mid-latitude and high-latitude UBs

To further explore the causes of the generation of mid-latitude (high-latitude) UBs, we create daily composites of instantaneous Z500 and SAT anomalies as well as WAF vectors for UB events during the blocking evolution process. Two-day-interval sequences of composite daily Z500 and SAT anomalies during the period from lag $-20$ to $2$ d are shown in figure 6 for mid-latitude and high-latitude UB events, where lag 0 denotes the peak day of the UB and the blue arrow
represents the WAF vector at 500 hPa. Although mid-latitude (high-latitude) UBs mainly take place during the period from lag $-10$ to $10$ d, North Atlantic blocking (Greenland blocking) can appear prior to the UB, from lag $-20$ to $-8$ d (figures 6(a) and (b)). It is found that North Atlantic blocking mainly occurs on the south side of Greenland, which peaks at lag $-18$ d and is still strong before lag $-20$ d (figure 6(a)). When this North Atlantic blocking decays from lag $-18$ to $-12$ d, the WAF vector points to the Ural region (figure 6(a)). Along with the disappearance of the North Atlantic blocking from lag $-8$ to $0$ d, an intensified WAF vector toward the Ural region is clearly seen, which subsequently leads to a mid-latitude UB via the propagation of wave trains from the North Atlantic midlatitudes to the Ural region. On the other hand, we can see that although the Greenland Ice Melts are always stronger for the high-latitude UBs than for the mid-latitude UBs. In contrast, the Greenland Ice Melts (figure 7(d)) are always stronger for the high-latitude UBs than for the mid-latitude UBs. Thus, the strong extratropical AMO+ SST (Greenland Ice Melt) anomalies are a favorable precursor of the North Atlantic blocking (Greenland blocking). We also noted that the SST anomalies over the BKS do not strongly depend on the evolution of UBs, because their temporal change is small regardless of whether UBs are present or absent (from lag $-20$ to $-10$ d) (figure 7(b)). In other words, the BKS
SST anomalies are not a response to UBs. Instead, they are more likely to be a driver of relatively weak stationary anticyclones over the BKS (figure 4(f)) as some part of the high-latitude UBs through increased surface heat fluxes (Zhang et al. 2018). In addition, it is noted that the variations of the BDL SST anomalies are unstable during the period prior to UBs and their difference between the mid-latitude and high-latitude UBs (figure 7(c)) is weaker than that of the extratropical North Atlantic or BKS SST anomalies, thus indicating that the role of the BDL SST anomalies seems to be weak in the establishment of UBs. We also see that the negative NAO index prior to the UB onset is larger for high-latitude UBs than for mid-latitude UBs (figure 7(e)). Thus, the presence of a strong NAO+ pattern resembling Greenland blocking can also be considered to be a precursor of high-latitude UBs.

We further show the time-mean composite daily Z500 and SAT, Greenland Ice Melt (meltwater production over Greenland) and SST anomalies averaged from lag $-20$ to $-10$ d during the period prior to UB in figure 8 to understand whether the mid-latitude (high-latitude) UBs are related to the presence of a strong precursor North Atlantic blocking (Greenland blocking). It can be seen from figure 8 that strong blocking anticyclones appear over the North Atlantic (Greenland) prior to the mid-latitude (high-latitude) UBs (figures 8(e)–(f), which corresponds to stronger (weaker) extratropical AMO+ SST anomalies over the North Atlantic (figures 8(c)–(d). For these cases, a prior negative (positive) SST anomaly is also seen over the BKS for the mid-latitude (high-latitude) UB, in agreement with the daily composite results in figure 7. In contrast, the Greenland Ice Melts prior to the onsets of UBs are stronger especially on the northeast side of Greenland’s landmass for the high-latitude UBs (figure 8(b)) than for the mid-latitude UBs (figure 8(a)). Thus, it is likely that the presence of prior North Atlantic blocking (Greenland blocking) is more closely related to strong prior extratropical AMO+ SST anomalies (Greenland Ice Melts). The numerical results of Ghosh et al. (2017, 2019) indicated that a strong extratropical AMO+ SST anomaly can reinforce a large-scale anticyclone resembling a North Atlantic blocking in the warm SST region through the forcing of the positive heat flux and Rossby wave source, which subsequently forms an east-west wave train from the North Atlantic to the Ural region. A strong Greenland Ice Melt has a similar effect, which can also reinforce a Greenland blocking, though Greenland blocking can be initiated by synoptic-scale eddies (Zhang and Luo 2020) or diabatic heating (Steinfeld and Pfahl 2019). Thus, a mid-latitude UB is, to some extent, mainly due to the forcing of a strong prior extratropical AMO+ SST anomaly, whereas a high-latitude UB is mainly due to the forcing of a strong prior Greenland Ice Melt.

4. Conclusions and discussions

In this paper, we have examined the conditions that favor heat waves over west Russia. The EOF analysis reveals that summer heat waves over west Russia...
Figure 8. Time-mean composite daily (a) and (b) Greenland Ice Melt (meltwater production over Greenland), (c) and (d) SST and (e) and (f) Z500 (contours; CI = 10 gpm) and SAT (color shading, unit: K) anomalies with the wave activity flux vector (e) and (f) denoted by the blue arrows averaged over the prior period from lag −20 to −10 d of (a), (c) and (e) midlatitude and (b), (d) and (f) high latitude UB events during 1979–2017. The dot (color shading) in panels a-d (e)–(f) denotes the region above the 95% confidence level for a two-sided student t-test.

exhibit two kinds of spatial patterns: mid-latitude and high-latitude heat wave types, in which the mid-latitude (high-latitude) heat waves are located on the southwest (northeast) side of the Ural Mountains. It is revealed that the two types of heat waves have different dynamic origins. The generation of the mid-latitude (high-latitude) Russian heat wave is mainly due to the maintenance of mid-latitude (high-latitude) UBs centered near 45°E and 50°N (65°E and 65°N). In the two types of blocking events, the mid-latitude UBs are shown to originate from the decay and energy dispersion of North Atlantic blocking associated with extratropical AMO$^+$ SST anomalies via wave train propagation, as revealed by the WAF of Takaya and Takaya (2001), whereas high-latitude UBs result from the decay and energy dispersion of Greenland blocking related to strong Greenland ice melting over Greenland’s landmass.

Moreover, we find that the positive (negative) anomalies of the BKS SSTs also play a role in the occurrence of UB events. When the BKS SST anomalies are positive (negative), slightly strong high-latitude (weak mid-latitude) UBs can easily occur to the east (west) of 60°E and to the north (south) of 60°N. Thus, mid-latitude Russian heat waves are mainly related to extratropical AMO$^+$ SST anomalies and negative BKS SST anomalies, whereas high-latitude Russian heat waves are mainly linked to strong Greenland ice melting and positive BKS SST anomalies. Daily composites further reveal that strong Greenland ice melts, positive BKS SST anomalies and strong NAO$^-$ are the precursors of high-latitude UBs leading to high-latitude Russian heat waves, whereas strong extratropical AMO$^+$ SST anomalies and negative BKS SST anomalies are the precursors of mid-latitude UBs leading
to mid-latitude Russian heat waves. These results are new findings, and differ from previous studies (e.g. Dole et al 2011, Trenberth and Fasullo 2012, Schneider et al 2012), which did not mention the cooperative effect of the North Atlantic SST anomalies or Greenland ice melts with the BKS SST anomalies on the generation of Russian heat waves in different regions.

However, it should be pointed out that here we only used the reanalysis data to examine the physical causes of Russian heat waves in different regions. Full simulation studies of numerical models are not covered by this paper. Thus, further model studies are needed, which can improve our understanding of how downstream Russian heat waves depend on the upstream GrIS and North Atlantic SST conditions, though our results above are partly supported by the numerical results of Ghosh et al (2019). Moreover, in a future study we should further consider the effects of low summer precipitation conditions on Russian heat waves.

Acknowledgments

The authors acknowledge support from the Chinese Academy of Science Strategic Priority Research Program (Grant XDA 19070403), the National Natural Science Foundation of China (Grant numbers: 41790473 and 41430533) and the National key research and development program of China (2016YFA0601802).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://apps.ecmwf.int/datasets/data/interim-full-daily/.

ORCID iD

Dehai Luo @ https://orcid.org/0000-0001-8834-8623

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