ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

Abstract

Atmospheric blocking (‘blocking’) in the Northern Hemisphere (NH) is a crucial driver of extreme cold spells in winter. Here we investigate the anthropogenic influence on the NH blocking and its impact on surface air temperature (SAT) during the winter 1960/1961–2012/2013 using two HadGEM3-GA6-N216 simulations with 15 ensemble members: (a) with anthropogenic and natural forcing (All-hist) and (b) with natural forcing only (Nat-hist). Compared to the Nat-hist run, the blocking frequency in the All-hist run decreases in the Euro-Atlantic, the Urals and the western Pacific, whereas it increases in the eastern Pacific and Greenland. These responses can be explained by the response of planetary waves and storm tracks. On the other hand, the decrease in SAT downstream of the blocking regions in the All-hist run is more pronounced than the Nat-hist run, especially in Europe and the Urals. Correspondingly, the proportion of cold days during all blocking days in these sectors is higher in the All-hist run than the Nat-hist run. These responses can be explained by the wind response associated with blocking. Overall, the spatiotemporal characteristics of blocking is crucial for evaluating the impact of blocking on extreme weather, and their response to anthropogenic forcing should be investigated by more models.

1. Introduction

Over the mid-latitude Northern Hemisphere (NH), a quasi-stationary large-scale anticyclonic system obstructs the prevailing westerly winds. The persistence of such an anticyclonic system for 5 d or more is called atmospheric blocking (‘blocking’) (Rex 1950, Tibaldi and Molteni 1990, Croci-Maspoli et al 2007). The development and decay of blocking are often accompanied by a sharp change in large-scale circulation and the occurrence of severe weather events (Buehler et al 2011, Masato et al 2012). The long-lived blocking events are often associated with extreme weather events, which may exert a significant impact on agriculture, economy and human health. For example, the recurrence of blocking events near the Ural Mountains was related to the long-lasting icy rain and heavy snowstorm over southern China in January 2008 (Zhou et al 2009). Climatologically, the blocking frequency has two peaks over the Euro-Atlantic and Pacific sectors and a 3rd peak located in the vicinity of the Ural Mountains (Barriopedro et al 2006, Diao et al 2006, Tyrlis and Hoskins 2008a, Cheung et al 2013, Chen et al 2020).

1 School of Physical Science and Technology, Yangzhou University, Yangzhou, People’s Republic of China
2 School of Atmospheric Sciences & Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, People’s Republic of China
3 Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People’s Republic of China
4 School of Geosciences, University of Edinburgh, Edinburgh, United Kingdom
5 Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University for Information Science and Technology, Nanjing, People’s Republic of China
6 Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
7 School of Atmospheric Sciences, Lanzhou University, Lanzhou, People’s Republic of China
8 Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing, People’s Republic of China

* Authors to whom any correspondence should be addressed.

E-mail: zhux53@mail.sysu.edu.cn and zhanghlan5@mail.sysu.edu.cn

Keywords: atmospheric blocking, cold extremes, anthropogenic forcing, global warming

Supplementary material for this article is available online
The intensity of blocking in winter (December–January–February) is usually stronger than in other seasons (Cheung et al. 2013, Masato et al. 2013, Qiao et al. 2020), and hence in this study we focus on winter blocking.

During the past few decades, both low- and high-temperature extremes in different seasons have warmed substantially (Brown et al. 2008, Donat et al. 2013, IPCC 2013). The temperature extremes are projected to warm further in the 21st century under stronger radiative forcing. Because of the relationship between blocking and extreme weather, it is crucial to evaluate the response of blocking and the associated extreme weather to anthropogenic forcing. Previous studies have shown a decrease in the NH blocking frequency in future climate scenarios with stronger radiative forcing (Dunn-Sigouin and Son 2013, Li et al. 2017a, 2017b, Woolings et al. 2018, Davini and D’Andrea 2020). This is linked to a strengthened upper-level westerly jet associated with an enhanced meridional temperature gradient between the tropics and the high-latitudes. The stronger westerly jet leads to less meandering flow that is less favorable for the occurrence of blocking (Lee and Ahn 2017). Meanwhile, due to the eastward extension of the westerly jet, the preferred location of blocking over the Eurasian continent may shift eastward (de Vries et al. 2013, Masato et al. 2014, Cheung and Zhou 2015). Indeed, there is only moderate confidence that blocking frequency will decrease, and the future impact of blocking on the regional climate is uncertain (Christensen et al. 2014). We have to improve our understanding about the current impact of anthropogenic forcing on blocking and the associated regional extreme weather.

During the past few decades, the NH winter blocking did not have an overall trend. Instead, the long-term variation of the blocking frequency has strong interannual and interdecadal variations, which is linked to the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation over the Atlantic, as well as the El Niño and Southern Oscillation and the Pacific Decadal Oscillation over the Pacific (Barriopedro et al. 2006, Rimbu et al. 2014, Kim and Ha 2015, Lupo et al. 2019). Regionally, Ural blocking (or called Asian blocking) has an increasing trend (Barnes et al. 2014, Wang and Chen 2014). Because the winter Ural blocking strengthens the warm air advections to the Arctic and cold air advections to the mid-latitude Eurasian continent (Luo et al. 2016, Tyrlis et al. 2020), the recent increasing trend of Ural blocking is associated with the ‘warm Arctic–cold Eurasia’ temperature trends (Kug et al. 2015, Luo et al. 2016, Chen et al. 2018, Ye et al. 2018, Freychet et al. 2020). This period coincides with the rapid decline of the Arctic sea ice cover. Stronger anthropogenic forcing likely enhances the loss of Arctic sea ice cover and the Arctic warming (Dai et al. 2019).

The occurrence of extreme cold events since late 2000s has also motivated more research analyzing the characteristics of cold extremes under the global warming background (Cattiaux et al. 2010, Wang and Chen 2010, Lee et al. 2015, Luo et al. 2015, Qiao et al. 2015). However, the impact of Arctic warming on the midlatitude circulation (including blocking) is still controversial. Whereas some studies suggested that the reduction of Arctic sea ice cover and the Arctic warming favor the occurrence of blocking-type circulation (Francis and Vavrus 2012, Mori et al. 2014), some studies suggested the opposite (Hassanzadeh and Kuang 2015, Blackport and Screen 2020). As mentioned previously, Ural blocking is associated with the ‘warm Arctic–cold Eurasian’ temperature anomaly pattern (Luo et al. 2016, Tyrlis et al. 2020). The recent Eurasian cooling may be contributed by natural forcing or internal variability (Zhang et al. 2012, Ogawa et al. 2018, Ye and Messori 2020). It is therefore valuable to assess the response of the NH winter blocking and its associated climate impact to anthropogenic forcing during the past few decades, which is the objective of this study.

In this study, we analyze the atmospheric general circulation model simulations of the Hadley Centre Global Environmental Model version 3 Global Atmosphere 6.0 (HadGEM3-GA6-N216, Walters et al. 2017, Qian et al. 2018) at the N216 resolution during the winter 1960/1961–2012/2013. We try to understand how the anthropogenic forcing influences (a) the blocking frequency, and (b) the cold weather associated with blocking events in the boreal winter.

2. Data and methods

2.1. Data

Due to data availability, the model outputs include only the daily fields of the 500 hPa geopotential height (Z500), the 850 hPa zonal and meridional components of wind (U850, V850), the surface air temperature (SAT) and the sea level pressure (SLP) of two HadGEM3-GA6-N216 simulations from the UK Met Office (Christidis et al. 2013, Walters et al. 2017, Ciavarella et al. 2018, Hao et al. 2019), with a horizontal resolution of 0.56° × 0.83° at 85 vertical levels. Such a horizontal resolution (<100 km) has a better performance in simulating the blocking frequency, especially the Euro-Atlantic sector (Schiemann et al. 2017).

The two HadGEM3 simulations have different boundary conditions. The 1st simulation is forced with the observed sea ice concentrations and sea surface temperature from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner 2003); it includes both anthropogenic and natural forcing and is named as All-hist run. The 2nd simulation is forced with natural forcing only, where the model estimate of the anthropogenic component are removed from the HadISST data; it is
named as All-hist run. The details of the estimation can be referred to Christidis et al. (2013), and a brief description is given in supplementary (available online at stacks.iop.org/ERL/16/094029/mmedia). The ensemble-mean in each run is taken as the unweighted averaged of 15 members. The difference in the winter climatology of SLP and SAT between the two simulations is shown in figure S1.

The simulation results are also compared to the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al 1996). These data have a horizontal resolution of $2.5^\circ \times 2.5^\circ$, except that SAT (2 m temperature) is on the T62 Gaussian grid. All numerical data are interpolated into $2.5^\circ \times 2.5^\circ$ prior to analysis.

2.2. Method

Blocking refers to the regions with a reversal in the geopotential height gradient over the extratropics (e.g. Tibaldi and Molteni 1990, Barriopedro et al 2006). The detection of blocking is briefly described below. Blocking regions are defined by the daily Z500 with more than five consecutive longitude grid points (i.e. >12.5 $^\circ$ longitude) at a calendar day, and these regions satisfy all of the three criteria in (1). Specifically, the 1st two equations in (1) are to check if a region has a reversal in the meridional gradient of Z500 (i.e. blocking-type circulation), whereas the 3rd equation in (1) is to check if the central part of the region is an anticyclone. The equation is written as:

$$Z_{500}(\lambda, \phi_N) - Z_{500}(\lambda, \phi_S),$$

where $Z_{500}(\lambda, \phi)$ is the 500 hPa geopotential height at latitude $\phi$ and longitude $\lambda$; $\phi_N$ ranges from 30$^\circ$ N to 72.5$^\circ$ N, $\phi_S = \phi_N + 15^\circ$ for the datasets with a horizontal resolution of $2.5^\circ$ latitude $\times 2.5^\circ$ longitude (Scherrer et al 2006). The term $Z_{500}(\lambda, \phi_N)$ in the third equation of (1) denotes the zonal mean of Z500 at the same latitude as $Z_{500}(\lambda, \phi_S)$. In the following, day +0 refers to the onset day of blocking events, whereas day $-n$ and day $+n$ refers to $n$ days prior to and after the onset of blocking events.

The study period includes the winters from 1960/1961–2012/2013. Following Chang (2009), storm tracks are defined as the root mean square value of the 2–6 d band-pass filtered SLP anomaly. At every grid, a day is called ‘cold day’ when the SAT is below the 5 d running mean of the 10th percentile in the same calendar day during the entire study period (Feng et al 2018). Statistical significance tests are computed by the two-tailed Student’s $t$-test.

3. Results

3.1. Blocking frequency

Figure 1(a) shows the climatology of NH blocking frequency during the winter 1960/1961–2012/2013 in the NCEP/NCAR reanalysis and the All-hist run. Consistent with previous studies (Scherrer et al 2006), the climatology has maxima over the Euro-Atlantic, Pacific and Greenland sectors, and the maximum in the Euro-Atlantic sector is extended eastward to the Urals (figure 1(a)). Such a spatial distribution is reproduced by the HadGEM3-GA6-N216 All-hist run, where the NH blocking frequency between the reanalysis and the ensemble mean of the All-hist run has a pattern correlation coefficient of +0.96 and a root mean square error of +0.89% (figure 1(a)). Compared to the reanalysis, the simulated blocking frequency in the All-hist run is overestimated over the eastern Pacific and underestimated over the Euro-Atlantic and Urals sectors (figure S2), where the negative bias in the Euro-Atlantic region is common in climate models (Scaife et al 2010, Dunn-Sigouin and Son 2013, Masato et al 2013). In response to anthropogenic forcing, the area-averaged blocking frequency decreases in Europe (45$^\circ$ N–60$^\circ$ N, 20$^\circ$ W–20$^\circ$ E), the Urals (50$^\circ$ N–70$^\circ$ N, 60$^\circ$ E–100$^\circ$ E), and the western Pacific (50$^\circ$ N–70$^\circ$ N, 110$^\circ$ E–150$^\circ$ E), whereas the blocking frequency increases in the eastern Pacific (55$^\circ$ N–72.5$^\circ$ N, 180$^\circ$ W–140$^\circ$ W) and Greenland (60$^\circ$ N–72.5$^\circ$ N, 55$^\circ$ W–15$^\circ$ W) (magenta boxes in figure 1(b); see table 1).

The occurrence of Euro-Atlantic blocking is related to the interaction between an extratropical cyclone under intensification and a planetary ridge (Lupo and Smith 1995). The peak of winter-time Euro-Atlantic blocking frequency is located at the exit of North Atlantic storm tracks (figure 1(a) vs figure 1(c)), suggesting a crucial role of storm tracks in the frequency of Euro-Atlantic blocking (Tyrlis and Hoskins 2008b, Luo et al 2010). Thus, the response of blocking frequency in the All-hist run can be explained by the response in the mean state of large-scale atmospheric circulation and storm tracks. In response to anthropogenic forcing, the increase in SAT is larger in the high-latitudes than the low-latitudes (figure S1). This is associated with a weaker meridional temperature gradient and a reduced lower-tropospheric baroclinicity, where the latter is related to weaker storm tracks (Harvey et al 2015). The substantial weakening of storm tracks over the northeastern Atlantic and the high-latitude Eurasia represent fewer extratropical cyclones traveling from the North Atlantic to Eurasia (figure 1(d)). Therefore, the weakened North Atlantic storm tracks inhibit the occurrence of blocking over the Euro-Atlantic and the Urals sectors.

On the other hand, the formation of North Pacific blocking and Greenland blocking is usually due to the interaction between high-frequency eddies.
Figure 1. The winter climatology in the All-hist run (left) (shaded) and the NCEP/NCAR reanalysis (contour), (right) the climatological difference between the All-hist run and the Nat-hist run (shaded) and the winter climatology in the All-hist run (contour). (a) and (b) The NH blocking frequency (%), (c) and (d) storm tracks (hPa²), (e) and (f) the 500 hPa eddy geopotential height (where the zonal mean is removed) (gpm). In the right panel, stippling indicates the 90% confidence level.
Table 1. The area-averaged blocking frequency in Europe, the Urals, the western Pacific, the eastern Pacific and Greenland (see magenta boxes in figure 1(b)) in the NCEP/NCAR reanalysis, the All-hist run and the Nat-hist run during the winter 1980/1981–2012/2013. In the 2nd and 3rd columns, the error term is the standard error of 15 ensemble members.

| Blocking frequency | Reanalysis | All-hist | Nat-hist |
|--------------------|------------|----------|----------|
| Europe             | 8.68%      | 6.91% ± 0.17% | 7.45% ± 0.11% |
| Ural               | 2.95%      | 2.38% ± 0.05% | 2.63% ± 0.09% |
| Western Pacific    | 2.56%      | 2.33% ± 0.04% | 2.61% ± 0.06% |
| Eastern Pacific    | 5.92%      | 5.83% ± 0.15% | 5.38% ± 0.10% |
| Greenland          | 5.76%      | 3.75% ± 0.13% | 3.44% ± 0.13% |

and the low-frequency background flow (Woollings et al 2008, Tyrlis and Hoskins 2008b, Hwang et al 2020). In response to anthropogenic forcing, both the storm tracks and the planetary trough over the western Pacific become weaker (figures 1(d) and (f)). These are associated with fewer occurrence of western Pacific blocking (figure 1(b)). Meanwhile, the planetary trough shifts eastward toward the eastern Pacific. The planetary ridge near Alaska and the storm tracks at ~30° N over the eastern Pacific become stronger (figures 1(d) and (f)). These favor more occurrence of eastern Pacific blocking (figure 1(b)), where the formation mechanism is similar to Euro-Atlantic blocking (Tyrlis and Hoskins 2008b). Outside the Pacific, a stronger planetary trough and ridge is located at the high-latitude North America and Greenland (figure 1(f)). In addition, due to a weaker meridional temperature gradient (figure S1), the climatological meridional geopotential gradient near Greenland is weaker. These mean-state changes favor more reversal of the geopotential gradient and a higher blocking frequency over Greenland (figure 1(b)).

3.2. Cold anomalies associated with blocking events

We also concern if blocking events under anthropogenic forcing exert a stronger or weaker impact on SAT anomalies. The SAT and SLP anomalies during the blocking events in the All-hist run are shown in the left panel of figure 2, whereas the difference in these anomalies between the two simulations is shown in the right panel of figure 2. Note that in the simulations and the NCEP/NCAR reanalysis the SAT and SLP anomalies associated with the blocking events have a similar spatial pattern (left panel in figures 2 and S3). In all blocking sectors, pronounced cold anomalies appear in the eastern and/or southern flanks of the blocking anticyclone, which are related to an enhanced cold air advection from the high latitudes (left panel in figures 2 and S3). We select one cold domain in each blocking sector in order to investigate the anthropogenic influence on cold anomalies during blocking days: Europe (40° N–55° N, 0° E–30° E), the Urals (45° N–60° N, 70° E–100° E), the western Pacific (30° N–45° N, 110° E–140° E), the eastern Pacific (45° N–60° N, 130° W–100° W), and Greenland (30° N–45° N, 80° W–50° W) (magenta boxes in figures 2 and S3). Note that in a specific sector (magenta box of figure 1(b)), a blocking day has at least 30 blocking grids within the sector, where these grids satisfy the criteria in equation (1).

The area-averaged SAT anomalies inside the cold domain of the All-hist run are lower than that of the Nat-hist run, where the difference is shown at the top right of figure 2. Figure 3 shows the day-to-day variation of such SAT anomalies during the blocking events. Prior to the development of blocking events, the SAT anomalies are small in magnitude. The difference in SAT anomalies between the All-hist run and the Nat-hist run is small in most blocking sectors. During the intensification of blocking events, the SAT drops abruptly, and the negative SAT anomalies last for more than 1 week. The decrease of SAT in the All-hist run is generally larger than the Nat-hist run, especially in Europe and the Urals, with a difference exceeding 0.6 °C and 0.7 °C (figures 3(a) and (b)). Note that the stronger temperature drop in the All-hist run is still apparent if the SAT anomalies are replaced by the raw SAT (figure S4).

When the proportion of cold days (i.e. SAT below the 10th percentile) during blocking in the All-hist run is compared to the Nat-hist run (figure 4), it is significantly larger downstream of the Euro-Atlantic, Urals and eastern Pacific sectors (figures 4(a), (b), and (d)). The cold days also slightly increase in the southwestern flank of western and Greenland blocking (figures 4(c) and (e)), which is influenced by the northerly wind of the cyclonic vortex of blocking. Recall that the Euro-Atlantic, Urals and western Pacific sectors have a lower blocking frequency in response to the anthropogenic forcing (figure 1(b)). Therefore, we should be aware the impact of blocking on extreme weather events. Although the blocking frequency may substantially decrease under the global warming, blocking may exert a stronger downstream impact, such as a stronger drop in SAT.

The stronger cooling associated with the blocking events in the All-hist run is depicted by the composite difference of the 500 hPa height anomalies and the 850 hPa wind anomalies between the All-hist run and the Nat-hist run (figure 5). As mentioned previously, over the Euro-Atlantic and Ural sectors, the development of blocking is associated with a ridge interacting with an extratropical cyclone travelling eastward from the North Atlantic. This is manifested as an eastward propagation of a Rossby wave packet (Nakamura et al 1997, Takaya and Nakamura 2005, Cheung et al 2013; see also figures S5(a) and (b)). In the All-hist run, the North Atlantic storm tracks are weaker (figure 1(d)), and the high-latitude North Atlantic has positive eddy
height anomalies (figure 1(f)). The former represents fewer passage of extratropical cyclones and a lower blocking frequency over the Euro-Atlantic and Ural sectors, as mentioned in section 3.1. The latter suggests a strong northward extension of the Euro-Atlantic ridge prior to the development of Euro-Atlantic blocking (figure 1(e)), because the positive height anomalies are located north of the climatological planetary ridge.

During the development of Euro-Atlantic blocking in the All-hist run, a stronger cyclonic flow occurs over the northwestern Atlantic (figures 5(a1) and (a2)). This accompanies a stronger anticyclonic flow over Scandinavia (figures 5(a1) and (a2)), inferring a
Figure 3. Evolution of the SAT anomalies (°C) from day $-9$ to day $+9$ relative to the onset of blocking events (day $+0$) in the NCEP/NCAR reanalysis (black line), the All-hist run (red line) and the Nat-hist run (blue line) in (a) Europe, (b) the Urals, (c) the western Pacific, (d) the eastern Pacific and (e) Greenland. In each plot, shading denotes the range of standard error in the All-hist run (gray) and the Nat-hist run (blue), and the domain is indicated at the top right.

stronger Rossby wavetrain across the North Atlantic. After the establishment of Euro-Atlantic blocking, the stronger anticyclonic flow persists over the European continent (figures S5(a3) and (a4)). The persistence of such an anomalous anticyclone enhances the cold air advection from the polar region to Europe, such that Europe has stronger cooling (figure 2(b)). Similarly, the development of Ural blocking in the All-hist run is associated with a stronger Rossby wavetrain propagating from the North Atlantic to the Urals, as inferred from a stronger cyclonic flow over the northeastern Atlantic and a stronger anticyclonic flow near the Urals (figures S5(b1)–(b3)). The persistence of such an anomalous anticyclone enhances the cold air advection from the polar region to the midlatitude Eurasian continent (figure 2(d)). Therefore, the stronger cooling of Euro-Atlantic and Ural blocking is related to a stronger Rossby wavetrain and a stronger anticyclone during the development stage.

Blocking over the western Pacific, the eastern Pacific and Greenland is characterized by a north high–south low dipole pattern (figures S5(c)–(e)). In the All-hist run, the western and eastern flank of Pacific and Greenland blocking is associated with an anomalous anticyclone and an anomalous cyclone (figures 2(f), (h), and (j)). During the development of western and eastern Pacific blocking, an anomalous anticyclone is located over the high-latitude
Asia (figures 5(c1) and (c2)). This region has a positive eddy height anomaly (figure 1(e)), representing a weaker planetary trough (figure 1(f)). Such an anomalous anticyclone coincides with the western flank of western Pacific blocking (figure 2(e)). The stronger anticyclone potentially advects more cold air from the polar region to Siberia, which reinforces the Siberian high (figure 5(c)). The associated cold air activity would bring cooling to lowers latitudes in East Asia (figure 2(e)). For eastern Pacific blocking, its western flank is located over the central-eastern North Pacific. The anomalous anticyclone over this region enhances warming over the northern flank of blocking (figure 5(d)). Moreover, the eastern flank of eastern Pacific blocking is located at the North American continent (figure S5(d)). The anomalous cyclone represents weakening of the northerly cold air advection from the high-latitudes (figure 5(d)). However, it is associated with stronger easterly wind from the Canadian Archipelago (figure 5(d)), which is a sea-ice region with temperature lower than the northern flank of eastern Pacific blocking. Such eastern wind brings more intense cold air masses from the sea-ice region to the northwestern America (figure 2(h)).

The occurrence of Greenland blocking results in cooling over Europe and part of the East Coast (i.e. the southwestern and northeastern flanks of blocking), where the cooling is due to the northerly wind from

Figure 4. Spatial distribution of the proportion of cold days in the blocking period in the All-hist run (contour interval 4%), and the difference in this quantity between the All-hist run and the Nat-hist run (shaded, %): (a) Europe, (b) the Urals, (c) the western Pacific, (d) the eastern Pacific and (e) Greenland. Stippling denotes the difference exceeding the 90% confidence level, and the area-averaged difference inside the yellow box is indicated at the top right.
Figure 5. Difference in the Z500 anomalies (shaded, gpm) and the 850 hPa wind anomalies (vector, m s$^{-1}$) between the All-hist run and the Nat-hist run from day −4 to day +4 relative to the onset of blocking events (day 0): (a1)–(a5) Europe, (b1)–(b5) the Ural, (c1)–(c5) the western Pacific, (d1)–(d5) the eastern Pacific and (e1)–(e5) Greenland. Note that the Z500 anomalies in the western Pacific and Greenland are multiplied by 0.5. Stippling indicates the Z500 anomalies exceeding the 90% confidence level.

the anticyclone and cyclone, respectively (figure 2(i)). In the All-hist run, the development of Greenland blocking is associated with an anomalous anticyclone over the North American continent and a north low–south high dipole anomaly over the Euro-Atlantic region (figure 5(e)). These infer a weaker intensification of Greenland blocking. The northerly wind of the slightly stronger anticyclone over North America causes slight cooling over the East Coast (figure 2(j)). Moreover, the weaker dipole over the North Atlantic does not induce pronounced temperature anomalies over Europe (figure 2(j)). The above results suggest that the changing impact of blocking under anthropogenic forcing depends on the spatiotemporal characteristics (e.g. geographic location and intensity) of blocking.

4. Discussion and conclusions

Previous studies mostly evaluate the influence of anthropogenic forcing on the northern winter blocking and its associated cold weather based on the future climate scenarios. Here, we assess this issue in the present climate using the HadGEM3-GA6-N216 simulations with 15 ensemble members for the winter 1960/1961–2012/2013; the model has a good performance in simulating the spatial distribution of blocking. Under the influence of anthropogenic forcing, the response of blocking frequency is closely related to the response of storm tracks and planetary waves. First, the decrease in blocking frequency over Euro-Atlantic and Urals is associated with weakening of the North Atlantic storm tracks. Second, the decrease in blocking frequency over the western Pacific and the increase in blocking frequency over the eastern Pacific are related to an eastward shift of the planetary wave. Third, the increase in blocking frequency over Greenland is associated with a stronger planetary ridge. These results are generally consistent with the long-term trend in the reanalysis datasets and future projections in the high emission scenarios (Davini and D’Andrea 2020). The only exception is Greenland blocking, which has a decreasing trend in current and future climate in contrast to an increase in our work. This should be investigated in future.

Moreover, it is interesting to see a stronger impact of blocking on cold weather under anthropogenic forcing. Whereas the SAT anomalies in the All-hist and Nat-hist runs are comparable during the development of blocking events, the SAT in the All-hist run has a larger drop than the Nat-hist run during the mature stage of blocking events, especially in the Euro-Atlantic and Urals sectors. Correspondingly, the proportion of cold days associated with the blocking events increase under anthropogenic forcing. The stronger downstream impact of Euro-Atlantic and Ural blocking on cold weather is due to a stronger anticyclone near a developing blocking anticyclone, which advects more cold air from the polar region to the mid-latitude Eurasian continent. Pacific and Greenland blocking highs become weaker under anthropogenic forcing. The western and eastern flank of Pacific and Greenland blocking highs are associated with an anomalous anticyclone and an anomalous cyclone. When the anomalous anticyclone is located over the continent, its associated northerly wind would advect cold air to the southern flank of blocking, such as East Asia in western Pacific blocking and...
the East Coast in Greenland blocking. The anomalous cyclone over the eastern flank of blocking is associated with easterly wind anomaly. This brings more intense cold air masses from the Canadian Archipelago for the eastern Pacific blocking. In short, the impact of blocking on cold weather depends on the wind direction that advects cold air, where the response of wind to anthropogenic forcing is related to the spatiotemporal characteristics of blocking events, such as the geographic location and intensity.

Based on the above results, when evaluating the impact of blocking on extreme weather, we should be aware the changing characteristics of blocking events, in addition to blocking frequency. In response to strong anthropogenic forcing, the upper-tropospheric jet is projected to become stronger and shift poleward, which is linked to a general decrease of the NH blocking frequency. Moreover, the jet stream and storm tracks shift eastward, which is linked to a smaller reduction or a slight increase in the blocking frequency over the eastern Pacific and part of Eurasian continent. Because blocking is a crucial driver of extreme weather in the extratropical region, it is important to assess how the large-scale atmospheric circulation changes affect the spatiotemporal characteristics of blocking events and the associated climate impact.

Our results offer physical insight into how the anthropogenic forcing affects the blocking frequency and the impact of blocking events on cold weather via modulating the large-scale planetary waves and storm tracks. However, the results are merely based on single atmospheric model (HadGEM3-GA6-N216). A better physical picture should be revealed by more models with good performance in simulating blocking.

**Data availability statement**

The NCEP/NCAR data were downloaded from https://psl.noaa.gov/data/index.html. The HadGEM3-GA6-N216 data were downloaded from http://portal.nersc.gov/c20c/data.html.

All data that support the findings of this study are included within the article (and any supplementary files).

**Acknowledgments**

The authors acknowledge the constructive comments provided by the editor and two anonymous reviewers. This study is supported by the National Key Research and Development Program of China (2017YFC1502300 and 2018YFC1507702), Guangdong Major Project of Basic and Applied Basic Research (2020B0301030004), the National Natural Science Foundation of China (41875096, 41905057, 41905003 and 42088101), the General Program of the Natural Science Foundation of Guangdong Province (2021A151012419) and the Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (311021009).

**ORCID iDs**

Shaobo Qiao https://orcid.org/0000-0001-8163-7027

Ho-Nam Cheung https://orcid.org/0000-0001-9014-7003

Nicolas Freychet https://orcid.org/0000-0003-2207-4425

**References**

Barnes E A, Dunn-Sigouin E, Masato G and Woolings T 2014 Exploring recent trends in Northern Hemisphere blocking Geophys. Res. Lett. 41 638–44

Barriopedro D, García-Herrera R, Lupo A R and Hernandez E 2006 A climatology of Northern hemisphere blocking J. Clim. 19 1042–63

Blackport R and Screen J A 2020 Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves Sci. Adv. 6 eaaay2880

Brown S J, Caesar J and Ferro C A T 2008 Global changes in extreme daily temperature since 1950 J. Geophys. Res. Atmos. 113 D05115

Buehler T, Raible C and Stocker T F 2011 The relationship of winter season North Atlantic blocking frequencies to extreme cold or dry spells in the ERA-40 Tellus 63A 212–22

Cattiaux J, Vautard R, Cassou C, Yioo P, Masson-Delmotte V and Codron F 2010 Winter 2010 in Europe: a cold extreme in a warming climate Geophys. Res. Lett. 37 L20704

Chang E K M 2009 Are band-pass variance statistics useful measures of storm track activity? Re-examining storm track variability associated with the NAO using multiple storm track measures Clim. Dyn. 33 277–96

Chen D, Qiao S, Tang S, Cheung H N, Liu J and Feng G 2020 Predictability of the strong Ural blocking event in January 2012 in the subseasonal to seasonal models of Europe and Canada Atmosphere 11 538

Chen L, Francis J and Hanna E 2018 The ‘warm-Arctic/ cold-continents’ pattern during 1901–2010 Int. J. Climatol. 38 S245–54

Cheung H H N and Zhou W 2015 Implications of Ural blocking for East Asian winter climate in CMIP5 GCMs. Part II: projection and uncertainty in future climate conditions J. Clim. 28 2217–33

Cheung H N, Zhou W, Mok H Y, Wu M C and Shao Y 2013 Revisiting the climatology of atmospheric blocking in the Northern Hemisphere Adv. Atmos. Sci. 30 397–410

Christensen J H et al 2014 Climate phenomena and their relevance for future regional climate change Climate Change 2013: The Physical Science Basis ed T F Stocker et al (Cambridge: Cambridge University Press) pp 1217–308

Christidis N, Stott P A, Scaife A A, Arribas A, Jones G S, Copsey D, Knight J R and Tennant W J 2013 A new HadGEM3-A-based system for attribution of weather-and climate-related extreme events J. Clim. 26 2756–83

Ciavarella A, Christidis N, Andrews M, Groensendiijk M, Rostron J, Elkington M, Burke C, Lott F C and Stott P A 2018 Upgrade of the HadGEM3-A based attribution system to high resolution and a new validation framework for probabilistic event attribution Weather Clim. Extrem. 20 9–32
Crocì-Maspoli, M, Schwierz, C and Davies, H C 2007 A multifaceted climatology of atmospheric blocking and its recent linear trend J. Clim. 20 633–49
Dai A, Luo D, Song M and Liu J 2019 Arctic amplification is caused by sea–ice loss under increasing CO2 Nat. Commun. 10 121
Davini, P and D’Andrea F 2020 From CMIP3 to CMIP6: Northern Hemisphere atmospheric blocking simulation in present and future climate J. Clim. 33 10021–38
de Vries H, Woolings T, Anstey J, Haarsma R J and Hazeleger W 2013 Atmospheric blocking and its relation to jet changes in a future climate Clim. Dyn. 41 2643–54
Diao Y, Li J and Luo D 2006 A new blocking index and its application: blocking action in the Northern Hemisphere J. Clim. 19 4819–39
Donat M G et al 2013 Updated analyses of temperature and precipitation extreme indices since the beginning of the 20th century: the HadEX2 dataset J. Geophys. Res. Atmos. 118 2098–118
Dunn-Sigouin, E and Son S W 2013 Northern Hemisphere blocking frequency and duration in the CMIP5 models J. Geophys. Res. Atmos. 118 1179–88
Feng, R, Yu R, Zheng H and Gan M 2018 Spatial and temporal variations in extreme temperature in Central Asia Int. J. Climatol. 38 e888–e900
Francis, J A and Vavrus S J 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes Geophys. Res. Lett. 39 106801
Freychet N, Tett S F B, Abatan A A, Schurer A and Feng Z 2020 Widespread persistent extreme cold events over South-East China: mechanisms, trends and attribution J. Geophys. Res. Atmos. 125 e2020JD035447
Hao X, He S, Wang H and Han T 2019 Quantifying the contribution of anthropogenic influence to the East Asian winter monsoon in 1960–2012 Atmos. Chem. Phys. 19 9903–11
Harvey B J, Shaffrey L C and Woolings T J 2015 Deconstructing the climate change response of the Northern Hemisphere wintertime storm tracks Clim. Dyn. 45 2847–60
Hassanzadeh, P and Kuang Z 2015 Blocking variability: arctic amplification versus Arctic oscillation Geophys. Res. Lett. 42 8596–95
Hwang J, Martineau P, Son S-W, Miyasaka T and Nakamura H 2020 The role of transient eddies in North Pacific blocking formation and its seasonality J. Atmos. Sci. 77 2453–70
IPCC 2013 Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (Cambidge: Cambridge University Press)
Kalnay E et al 1996 The NCEP/NCAR 40 year reanalysis project Bull. Am. Meteorol. Soc. 77 377–407
Kim S-H and Ha K-J 2015 Two leading modes of Northern Hemisphere blocking variability in the boreal wintertime and their relationship with teleconnection patterns Clim. Dyn. 44 2479–91
Kug J-S, Jeong J-H, Jang Y-S, Kim B-M, Folland C K, Min S-K and Son S-W 2015 Two distinct influences of Arctic warming on cold winters over North America and East Asia Nat. Geosci. 8 759–62
Lee D Y and Ahn J-B 2017 Future change in the frequency and intensity of wintertime North Pacific blocking in CMIP5 models Int. J. Climatol. 37 2765–81
Lee M, Hong C-C and Hsu H-H 2015 Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013–2014 boreal winter Geophys. Res. Lett. 42 1612–8
Li Y, Ye P, Feng J, Lu Y, Wang J and Pu Z 2017b Simulation and projection of blocking highs in key regions of Eurasia by CMIP5 models J. Meteorol. Soc. Japan Ser. II 95 147–65
Li Y, Ye P, Pu Z, Feng J, Ma B and Wang J 2017a Historical statistics and future changes in long-duration blocking highs in key regions of Eurasia Theor. Appl. Climatol. 130 1195–207
Luo D, Xiao Y, Yao Y, Dai A, Simmonds I and Franzke C L E 2016 Impact of Ural blocking on winter warm Arctic–cold Eurasian anomalies. Part I: blocking-induced amplification J. Clim. 29 3925–47
Luo D, Yao Y, Dai A and Feldstein S B 2015 The positive North Atlantic oscillation with downstream blocking and Middle East snowstorms: the large-scale environment J. Clim. 28 6398–418
Luo D, Zhou W and Wei K 2010 Dynamics of eddy-driven North Atlantic oscillations in a localized shifting jet: zonal structure and downstream blocking Clim. Dyn. 34 73–100
Lupo A R, Jensen A D, Mokhov I I, Timazhez A V, Eichler T and Efe B 2019 Changes in global blocking character in recent decades Atmosphere 10 92
Lupo A R and Smith F J 1995 Planetary and synoptic-scale interactions during the life cycle of a mid-latitude blocking anticyclone over the North Atlantic Tellus 47A 575–96
Masato G, Hoskins B J and Woolings T J 2012 Wave breaking characteristics of midlatitude blocking Q. J. R. Meteorol. Soc. 138 1285–96
Masato G, Hoskins B J and Woolings T 2013 Winter and summer Northern Hemisphere blocking in CMIP5 models J. Clim. 26 7044–59
Masato G, Woolings T and Hoskins B J 2014 Structure and impact of atmospheric blocking in the Euro-Atlantic region in present-day and future simulations Geophys. Res. Lett. 41 1051–8
Mori M, Watanabe M, Shigama H, Inoue J and Kimoto M 2014 Robust Arctic sea–ice influence on the frequent Eurasian cold winters in past decades Nat. Geosci. 7 869–73
Nakamura H, Nakamura M and Anderson J L 1997 The role of high- and low-frequency dynamics in blocking formation Mon. Wea. Rev. 125 2074–93
Ogawa F et al 2018 Evaluating impacts of recent Arctic sea ice loss on the northern hemisphere winter climate change Geophys. Res. Lett. 45 3255–63
Qian C, Wang J, Dong S, Yin H, Burke C, Ciavarella A, Dong B, Freychet N, Lott F and Tett S 2018 Human influence on the record-breaking cold event in January of 2016 in Eastern China Bull. Am. Meteorol. Soc. 99 5118–5122
Qiao S, Gong Z, Feng G and Qian Z 2015 Relationship between cold winters over northern Asia and the subsequent hot summers over mid-lower reaches of the Yangtze River valley under global warming Atmos. Sci. Lett. 16 479–84
Qiao S, Zhou M, Cheung H N, Zhou W, Li Q, Feng G and Dong W 2020 Predictability of the wintertime 500 hPa geopotential height over Ural–Siberia in the NCEP climate forecast system Clim. Dyn. 54 1593–606
Rayner N A 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res. Atmos. 108 4407
Rex D F 1950 Blocking action in the middle troposphere and its effects upon regional climate. II. The climatology of blocking action Tellus 2 275–301
Rimbu N, Lohmann G and Ionita M 2014 Interannual to multidecadal Euro-Atlantic blocking variability during winter and its relationship with extreme low temperatures in Europe J. Geophys. Res. Atmos. 119 13621–36
Sciffe A, Woolings T, Knight J, Martin G and Hinton T 2010 Atmospheric blocking and mean biases in climate models J. Clim. 23 6143–52
Scherrer S, Croci-Maspoli, M, Schwierz, C and Appenzeller C 2006 Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region Int. J. Climatol. 26 233–49
Schimmann R, Demory M-E, Shaffrey L C, Strachan J, Vidale P L, Mizielinski M S, Roberts M, Matsueda M, Wehner M F and Jung T 2017 The resolution sensitivity of Northern Hemisphere blocking in four 25 km atmospheric global circulation models J. Clim. 30 337–58
Takaya K and Nakamura H 2005 Geographical dependence of upper-level blocking formation associated with
intraseasonal amplification of the Siberian high J. Atmos. Sci. 62 4441–9
Tibaldi S and Molteni F 1990 On the operational predictability of blocking Tellus A 42 343–65
Tyrlis E, Bader J, Manzini E, Ukita J, Nakamura H and Matei D 2020 On the role of Ural blocking in driving the warm
Arctic–cold Siberian pattern Q. J. R. Meteorol. Soc. 146 2138–53
Tyrlis E and Hoskins B J 2008a Aspects of a Northern Hemisphere atmospheric blocking climatology J. Atmos. Sci. 65 1638–52
Tyrlis E and Hoskins B J 2008b The morphology of Northern Hemisphere blocking J. Atmos. Sci. 65 1653–65
Walters D et al 2017 The met office unified model global atmosphere 6.0/6.1 and jules global land 6.0/6.1 configurations Geosci. Model Dev. 10 1487–520
Wang L and Chen W 2010 Downward Arctic oscillation signal associated with moderate weak stratospheric polar vortex and the cold December 2009 Geophys. Res. Lett. 37 L09707
Wang L and Chen W 2014 The East Asian winter monsoon: re-amplification in the mid-2000s Chin. Sci. Bull. 59 430–6
Woollings T, Barriopedro D, Methven J, Son S-W, Martius O, Harvey B, Sillmann J, Lupo A R and Seneviratne S 2018 Blocking and its response to climate changeCurr. Clim. Change Rep. 4 287–300
Woollings T, Hoskins B, Blackburn M and Berrisford P 2008a A new Rossby wave-breaking interpretation of the North Atlantic oscillation J. Atmos. Sci. 65 609–26
Ye K, Jung T and Semmler T 2018 The influences of the Arctic troposphere on the midlatitude climate variability and the recent Eurasian cooling J. Geophys. Res. Atmos. 123 10162–84
Ye K and Messori G 2020 Two leading modes of wintertime atmospheric circulation drive the recent warm Arctic–cold Eurasia temperature pattern J. Clim. 33 3565–87
Zhang X, Lu C and Guan Z 2012 Weakened cyclones, intensified anticyclones and recent extreme cold winter weather events in Eurasia Environ. Res. Lett. 7 044044
Zhou W, Chan J, Chen W, Ling I, Pinto J G and Shao Y 2009 Synoptic-scale controls of persistent low temperature and icy weather over southern China in January 2008 Mon. Weather Rev. 137 3978–91