Implications of Ural Blocking for East Asian Winter Climate in CMIP5 GCMs. Part II: Projection and Uncertainty in Future Climate Conditions

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(Manuscript received 29 April 2014, in final form 5 November 2014)

ABSTRACT

Multiple model ensembles (MMEs) of Ural blocking frequency in 20 CMIP5 GCMs show no apparent increase or decrease in RCP4.5 and 8.5 runs throughout the twenty-first century. However, a significant increasing or decreasing trend of the Ural blocking index (UBI) is identified in individual GCMs, and the trend appears to be correlated with the trend of the Siberian high index (SHI), which measures the East Asian winter climate. Regression analyses reveal that the trend of UBI is related to upstream circulation over the Euro-Atlantic region, such as the intensification of the Atlantic jet stream and the propagation of a quasi-stationary Rossby wave across Eurasia.

In the late twenty-first century, the year-to-year variation of UBI appears to show a stronger linkage with the large-scale circulation over the Kara and Laptev Seas. Meanwhile, UBI likely exerts a stronger impact on East Asia on synoptic and seasonal time scales. The uncertainty of UB might present a challenge for accurate prediction of the subseasonal and long-term variation of the East Asian winter climate. To further evaluate the uncertainty in projections of UB, additional work should assess the atmospheric response to the sea surface temperature over the Atlantic and the reduction of sea ice.

1. Introduction

Climatologically, the frequency of Northern Hemisphere blocking is higher in the extended winter season. As a function of longitude, blocking frequency features a bimodal distribution peaking over the Euro-Atlantic region and the Pacific Ocean, both of which are located downstream of the climatological storm tracks (e.g., Rex 1950; Tibaldi and Molteni 1990; Lupo and Smith 1995; Pelly and Hoskins 2003; Barriopedro et al. 2006; Tyrlis and Hoskins 2008a). In addition, the Ural Mountains (western Russia) are a secondary blocking sector, and blocking occurs over this region is called Ural blocking (UB) in the literature. The occurrence of UB is related to the eastward shift of storm activity over the Euro-Atlantic region in boreal winter (Diao et al. 2006; Tyrlis and Hoskins 2008b; Luo et al. 2010; Cheung et al. 2013). Under a warming climate, the blocking frequency likely decreases over the Euro-Atlantic and Pacific sectors and undergoes no apparent change or a slight increase over the Ural Mountains (Dunn-Sigouin and Son 2013; Masato et al. 2013). Yet, there have been limited studies analyzing the implications of blocking for the present and future regional climate (Masato et al. 2014; Woollings et al. 2014).

The objective of our work is to systematically evaluate the impact of wintertime UB on the East Asian winter climate. In Part I of this work (Cheung and Zhou 2015, hereinafter Part I), we demonstrated the ability of 25 GCMs participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) to simulate the linkage between UB and the East Asian winter climate in the historical run (HIST), which agrees with earlier observational work (e.g., Takaya and Nakamura 2005; Zhou et al. 2009; L. Wang et al. 2010; Cheung et al. 2012; Cheung et al. 2013). Basically, the occurrence of UB strengthens the advection of cold polar air toward western Siberia and reinforces the Siberian high (SH) near the surface. Because of the persistence of blocking in the extratropical atmosphere, UB potentially triggers severe cold air outbreaks or even persistent snowstorms in East Asia, where the impact can be large in the subtropical regions. For example, the extraordinarily high UB frequency in January 2008 was one of the dynamic
causes of an unusually long icy rain event and severe snowstorm in southern China (Zhou et al. 2009). Given the crucial role of UB in the East Asian winter climate, the projection of UB in the state-of-the-art CMIP5 GCMs may be vital for the government and policy makers in improving preparedness for cold extremes in East Asia even under a warming climate.

Compared to earlier generations of GCMs, the CMIP5 GCMs do not show great improvement in the simulation of blocking. As mentioned in chapter 14 of the IPCC Fifth Assessment Report (AR5; Christensen et al. 2014), there is medium confidence that blocking frequency will not increase, and the impact of blocking on the regional climate remains uncertain. Undoubtedly, the uncertainties in the occurrence of blocking could present a great challenge for assessing regional climate change, especially the occurrence of extreme weather. These uncertainties should be identified before further work is carried out in order to increase our confidence in projecting the future changes of blocking frequency.

It is reasonable to assume that climate change in the twenty-first century is a result of anthropogenic forcing superimposed on natural variability. Whereas natural forcing consists of strong interannual and multidecadal signals, anthropogenic forcing is a slowly varying signal. In Part II we attempt to investigate how likely it is that the long-term mean and variance of UB will undergo systematic changes and to determine whether these changes are related to changes in the East Asian winter circulation in the future climate scenarios. The results in Part II are derived from two of the representative concentration pathways (RCPs), the RCP4.5 and RCP8.5 scenarios (Moss et al. 2010), where the value denotes the strongest radiative forcing (W m$^{-2}$) in the twenty-first century. If the long-term mean of the large-scale circulation varies in a similar manner and differs only in magnitude between the two scenarios, then we can deduce the role of anthropogenic forcing in the basic state of the large-scale circulation. On the other hand, if the projection exhibits a large spread across individual GCMs, we will attempt to identify the cause of the uncertainty.

We seek to answer the questions below based on multiple model ensembles (MMEs) and the spread of 20 GCMs in the RCP4.5 and RCP8.5 scenarios:

- Will there be any systematic and significant changes in the frequency of Ural blocking?
- What are the possible causes for the future changes of UB?
- What will be the likely implication of UB for the East Asian winter climate?

The paper is organized as follows. The data and methods are described in section 2. Section 3 focuses on the UB frequency in RCP4.5 and 8.5 runs. Section 4 analyzes the long-term mean and variance trends of the UB frequency and the Siberian high intensity (SHI). Section 5 evaluates the implication of UB for East Asian winter. Finally, the results are summarized and discussed in section 6.

2. Data and methods

a. Data

We analyze the outputs of 20 CMIP5 GCMs where daily data are available in the historical (HIST), RCP4.5, and RCP8.5 runs, as summarized in Table 1. The data were extracted from the Earth System Grid Federation (ESGF) data portal (http://pcmdi9.llnl.gov/esgf-web-fe/). The raw data include daily and monthly fields of mean sea level pressure (MSLP), 250-hPa and 500-hPa zonal wind (U250 and U250), and 500-hPa geopotential height (Z500). To be consistent with Part I, we bilinearly interpolated the CMIP5 data into a horizontal resolution of 2.5° latitude × 2.5° longitude.

The entire study period for future climate conditions is December–February (DJF) from 2006 to 2099, where 2006 represents the DJF period from 2006 to 2007. The present climate condition is based on the 30-yr period of 1971–2000.

b. Detection of blocking

The blocking detection algorithm is briefly described below, where a detailed description can be referred to section 2b of Part I. First, at each grid point ($\lambda$, $\phi$), two zonal index equations (ZIN and ZIS) are used to determine whether the flow is blocking or nonblocking type on a calendar day ($t$) using the daily Z500 field (Lejenäs and Øakland 1983; Tibaldi and Molteni 1990):

$$ZIN(\lambda, \phi_0, t) = [Z500(\lambda, \phi_N, t) - Z500(\lambda, \phi_S, t)] / (\phi_N - \phi_S),$$  \hspace{1cm} (1)

$$ZIS(\lambda, \phi_0, t) = [Z500(\lambda, \phi_0, t) - Z500(\lambda, \phi_S, t)] / (\phi_0 - \phi_S),$$  \hspace{1cm} (2)

where

$$\lambda \in [0, 357.5]^\circ E,$$

$$\phi_N = 80^\circ N + \Delta,$$

$$\phi_0 = 60^\circ N + \Delta,$$

$$\phi_S = 40^\circ N + \Delta,$$

$$\Delta = (-5, -2.5, 0, 2.5 \text{ or } 5)^\circ \text{latitude}.$$

Here, $\phi_N$, $\phi_0$, and $\phi_S$ are northern, central, and southern latitude grid points to compute ZIN and ZIS.
A variation of 5° latitude ($\Delta$) is accepted due to spatial and seasonal variations of blocking locations. Note that $\Delta$ in this study is different from Tibaldi and Molteni’s (1990) study, which is due to the difference of the data resolution.

A blocking-type circulation at $\lambda$ (“blocking longitude”) is characterized by the reversal of the daily meridional Z500 gradient over the extratropical region. This has to be satisfied by $\text{ZIN} < -10 \text{ gpm (lat)}^{-1}$ and $\text{ZIS} > 0$.

Second, a blocking region consists of at least five consecutive blocking longitude grid points (12.5° longitude) because blocking is a large-scale system. The longitude and latitude center of a blocking region ($\lambda_{\text{ctr}}, \phi_{\text{ctr}}$) is defined as the grid with the largest positive Z500 anomaly within the region.

Third, only the blocking regions persisting for at least four consecutive days are retained, and these are called blocking events. The persistence criterion is determined by the characteristic time of the blocking region (Pelly and Hoskins 2003).

Fourth, the blocking frequency at each longitude in a period (say, DJF) is counted as the number of days in which a blocking event can be identified over that longitude throughout the period.

c. Ural blocking and Ural blocking index

In each winter, the UB frequency is taken as the DJF-averaged blocking frequency over 45°–90°E, which is called the Ural blocking index (UBI). The climatological statistics of UBI, including the long-term mean and variance, are derived from the UBI of individual winters.

The spatiotemporal characteristics are analyzed by the composites of UB events. Wintertime UB events are defined as those events whose centered longitude ($\lambda_{\text{ctr}}$) is located at 45°–90°E during their establishment (day 0). Furthermore, all of these events should start in the DJF period.

d. Siberian high intensity

As mentioned in section 2d of Part I, the East Asian winter climate is depicted by the Siberian high intensity. It is defined as the area-averaged MSLP over 40°–65°N, 80°–120°E, which encloses the climatological region of the SH.

e. Projection in the twenty-first century

Considering a period of 30 years to be the most common length to define the climatology (e.g., 1961–90,
1971–2000, and 1981–2010), a 30-yr sliding window is applied for the period 2006–2100 in the RCP runs to project the long-term mean and variance. To test whether the changes in blocking frequency and large-scale circulation features are systematic and statistically significant in different periods of the twenty-first century, the projection and uncertainty analyses are assessed by the running difference, the time-slice difference, and the trend of the long-term mean and variance:

- The running difference is carried out for the 65 running means of a time series throughout the entire study period, where the first period is 2006–35 and the last is 2070–99.
- The time-slice difference is used for composite and regression analyses, which are based on three 30-yr base periods: (i) 2010–39, (ii) 2040–69, and (iii) 2070–99.

The trend of the long-term mean and variance is obtained by the linear regression of the 30-yr running mean and variance against time. The trend is considered to be robust if the sign is the same in at least 75% of the GCMs (i.e., 15 out of 20 GCMs).

3. Frequency of UB occurrence

To identify the most notable change in response to anthropogenic forcing, the MME of the blocking frequency climatology in the RCP4.5 and RCP8.5 runs is shown together with the HIST run and NCEP data in Fig. 1. In the HIST run, although the majority of the CMIP5 models can reproduce the bimodal blocking frequency distribution over the Northern Hemisphere, the primary peak over the Euro-Atlantic sector becomes much weaker and the secondary peak over the Ural Mountains appears to be more distinctive when compared to NCEP. As discussed in section 7b of Part I and in Scaife et al. (2010), this discrepancy is due to biases in the long-term mean circulation over the Euro-Atlantic region.
In the two RCP runs, the 65 MMEs of the 30-yr climatology from 2006–35 to 2070–99 are illustrated by a map with 65 different colors. Whereas the bimodal distribution remains unchanged (Figs. 1a,b), the mean blocking frequency over the two climatological peaks decreases systematically in the twenty-first century, and such a decrease is more pronounced in the Pacific sector and in the RCP8.5 run (Figs. 1c,d). This is consistent with previous studies analyzing the change of blocking frequency (Matsueda et al. 2009; Dunn-Sigouin and Son 2013; Masato et al. 2013). Over the Ural sector, however, there is no significant change in any period in the two RCP runs. Whereas the MME of UB frequency decreases slightly during the entire period of the RCP4.5 run, it increases slightly in the RCP8.5 run over the western and eastern boundary of the UB sector in the middle and late twenty-first century.

Because the blocking occurrence in a GCM is closely related to the climatological mean state of the GCM (Scaife et al. 2010), the change in the mean blocking occurrence over various sectors can be deduced by U500, as shown in Fig. 2. Compared to the HIST run, no significant change in U500 can be seen in the period 2010–39 (Figs. 2a,b). In the later periods, U500 exhibits a stronger tendency in the midlatitudes (south of \( \phi_N \)) and a weakening tendency in the subpolar region (north of \( \phi_N \)) over the North Pacific and Euro-Atlantic sectors (Figs. 2c–f), where these changes are more apparent in the period 2070–99 (Figs. 2e,f). The above changes suggest that there are 1) a weaker climatological meridional gradient of Z500 between \( \phi_N \) and \( \phi_0 \) and a less negative tendency of ZIN in Eq. (1), and 2) a stronger climatological meridional gradient of Z500 between \( \phi_0 \) and \( \phi_S \) and a stronger negative tendency of ZIS in Eq. (2). Because blocking has to be achieved by ZIN \( < -10 \text{ gpm (lat)}^{-1} \) and ZIS \( > 0 \), these tendencies are related to a decrease of blocking frequency over the Euro-Atlantic and Pacific sectors. On the other hand, U500 over the latitudes defining UB does not show a significant change in any period (Fig. 2). Based on the MME of the climatological mean state, the UB frequency is not likely to increase or decrease significantly in the twenty-first century.

The MME and the spread of the long-term mean of the UBI are shown in Figs. 3a and 3b. In the entire study period, although the MME is fairly constant (\( \sim 6\% \) of winter days; Figs. 3a,b) and is comparable to the HIST run (Figs. 3c,d), a large spread exists across the 20 CMIP5 GCMs. Such a spread might be partially related to the spread of large-scale circulation features over the Euro-Atlantic sector, as mentioned in Part I. Moreover, the difference in the long-term mean of UBI between the RCP runs and the HIST run also has a notable spread across the 20 CMIP5 GCMs (Figs. 3c,d), where the magnitude appears to be larger in the RCP8.5 run (Fig. 3d). The larger spread of the RCP8.5 run is probably due to the atmospheric response of different GCMs to the effect of climate change, including the long-term mean and variance of UBI, which will be investigated in section 4.

### 4. Trend of UBI and SHI

In boreal winter, the occurrence of UB is accompanied by the intensification of the SH. During the HIST period, a lower occurrence of UB in a given winter likely corresponds to a weaker SH and a warmer East Asian winter climate, and vice versa (L. Wang et al. 2010). In the two RCP runs, the long-term relationship between UB and the SH is studied by using the 30-yr running correlation between UBI and SHI throughout the twenty-first century, where each model has 65 linear correlation coefficients from 2006–35 to 2070–99 (Fig. 4). Although the running correlation of the two RCP runs has a large spread across the 20 CMIP5 GCMs, the majority of the GCMs have a significant correlation coefficient at the 95% confidence level throughout the twenty-first century (Fig. 4). This suggests a stable long-term relationship between UBI and SHI in the two RCP runs. Accordingly, we would like to address whether there is any relationship between the trend of UBI (representing the UB frequency) and SHI (as a proxy of the East Asian winter climate) in the future climate conditions.

#### a. Long-term mean

In section 3, based on the results of MME, we do not identify any robust changes of the UB frequency, unlike the remarkable decrease of the blocking frequency over the Euro-Atlantic and Pacific sectors. On the other hand, the mean state of the East Asian winter climate is expected to undergo a weakening trend under the global warming trend, which results from the weakened land-sea thermal contrast between the East Asian continent and the Pacific Ocean (Hu et al. 2000). The inconsistency of the MME trends of the long-term mean of UBI and SHI can be seen in Figs. 5a and 5b: whereas the weakening trend of SHI is pronounced in both runs, the trend of UBI is insignificant in the RCP4.5 run and positive in the RCP 8.5 run.

Although the MME trend of UBI does not follow that of SHI, the two trends across the 20 GCMs in the RCP8.5 run appear to be closely related to each other. When the trend of the 30-yr running mean of SHI is plotted against that of UBI across the GCMs (Fig. 6a), we obtain a statistically significant relationship between the two long-term means. The long-term mean trend of
SHI in a given GCM tends to be positive (negative) when the long-term mean trend of UBI exhibits a strong positive (negative) trend. It is noteworthy that five of the GCMs show a significant positive trend of SHI (Fig. 6a), in contrast to a remarkable weakening trend of the MME (Fig. 5b). Four of the five GCMs also show a positive trend of UBI (Fig. 6a). The above result suggests that the projection uncertainty of UBI might affect that of SHI.

It is necessary to depict the trend of large-scale circulation features related to the trend of UBI in order to deduce whether the trend of UBI and SHI could be...
linked. As shown in Figs. 7a,c,e, the trend of the 30-yr running mean of UBI is regressed against that of large-scale parameters (MSLP, Z500, and U250) across the 20 CMIP5 GCMs in the RCP 8.5 run. Associated with a larger long-term mean trend of UBI in a given GCM, positive and negative regression coefficients can be found over the SH and the Aleutian low (160°–170°E) near the surface in the GCM (Fig. 7a), corresponding to Fig. 3. Time series of 30-yr running mean of Ural blocking index for the MME (black) and the spread (shading) of 20 CMIP5 GCMs. (a),(b) Year-to-year variation in the RCP runs, where the gray lines represent the long-term mean and ±1 standard deviation of the UBI obtained from the 20 CMIP5 GCMs for the period 1971–2000. (c),(d) Difference between the RCP runs and the long-term mean in the HIST run of each GCM. Unit: % of winter days.

Fig. 4. Time series of 30-yr moving correlation between UBI and SHI in the MME (black solid line) and the spread across the 20 CMIP5 GCMs (shading) of the (a) RCP4.5 and (b) RCP8.5 runs. The black dashed line indicates the 95% confidence level with 29 degrees of freedom.
a stronger trend of the mean state of the East Asian winter climate, and vice versa. Furthermore, the regression coefficients of the trend of Z500 are positive north of 45°N and negative south of 45°N in the extratropical region (Fig. 7c). Because the Z500 mainly decreases with latitude, the regression map of Z500 seems to imply that the GCMs showing a positive trend of UBI have a weaker trend in the meridional gradient of Z500 over the midlatitudes, and vice versa.

Specifically, the positive trend of UBI is likely associated with the positive trend of Z500 near the Urals and the negative trend of Z500 near the Mediterranean Sea (~30°E; Fig. 7c). These trends are accompanied by the weakening trend of U250 south of the UB sector and the strengthening trend of U250 southeast of the Mediterranean Sea (Fig. 7e). The difference in the trends of U250 between the GCMs with an opposite trend of UBI is further depicted in Fig. 8. Comparatively, the GCMs showing a negative trend of UBI tend to have a stronger strengthening trend of U250 over the midlatitudes (Fig. 8b). These GCMs also tend to have a stronger weakening trend of U250 southeast of the Mediterranean Sea. As a result, the trends of these GCMs likely contribute to the significant regression coefficients of the trend of U250 upstream of the Urals in Fig. 7e. In addition, the positive trend of U250 attains a maximum over the North Atlantic and extends northeastward toward Europe (Figs. 8a,b), which are more pronounced in the GCMs showing a negative trend of UBI (Fig. 8b). Hence, the trend of U250 in Fig. 7e is related to the future change of the Atlantic jet stream (Barnes and Polvani 2013). In other words, the change in the long-term mean of UBI is closely related to the change in the climatological mean state, as discussed in Scaife et al. (2010).

b. Long-term variance

In addition to the trend of the long-term mean, it is also valuable to investigate the trend of the long-term

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**Fig. 5.** Time series of 30-yr (a),(b) running mean and (c),(d) running variance of (black solid line) UBI and (gray solid line) SHI in the (left) RCP4.5 and (right) RCP8.5 runs. The linear trend is represented by the dotted line, and its level of significance using the least squares fit is shown at the top left for UBI and at the top right for SHI.
variance of UBI and SHI, where the positive sign of the trend suggests a larger year-to-year variability in the late twenty-first century. As shown in Figs. 5c and 5d, the MME trend of the long-term variance of UBI is opposite in sign in the two RCP runs, being negative in the RCP4.5 run and positive in the RCP8.5 run. The variance trend of SHI, on the other hand, is insignificant in the RCP4.5 run and positive in the RCP8.5 run. In contrast to the consistent weakening of the long-term mean trend of SHI in the two RCP runs, the sign of its long-term variance trend is not consistent between the two RCP runs, suggesting a lower confidence in projecting the interannual variability of SHI.

In the RCP8.5 run, the trends of the long-term variance of UBI and SHI tend to be positive, and these trends seem to be moderately correlated across the 20 GCMs (Fig. 6b). When the long-term variance trend of UBI is regressed against that of MSLP and Z500 across the GCMs, alternating positive and negative regression centers appear across Eurasia (Figs. 7b,d). On one hand, both Z500 and MSLP have a positive center over the Atlantic, a negative center over Scandinavia, and another positive center over the Ural–Siberia region (Figs. 7b,d). Downstream of the UB sector, on the other hand, the regression coefficient of MSLP is positive and extends southeastward over the climatological SH region (Fig. 7b). In addition, the regression coefficient of Z500 is negative east of Lake Baikal (~120°E) and positive in the vicinity of Japan (~130°–140°E), where the latter is centered over the climatological East Asian trough region (Fig. 7d). These regression maps suggest that the long-term variance trend of UBI is related to the quasi-stationary Rossby wave train signal propagating from the Euro-Atlantic region to the Urals, and such a signal further propagates from the Urals to East Asia and the western North Pacific.

The positive trend of the long-term variance of UBI is further studied by the long-term mean and variance trends of MSLP (Fig. 9). In Fig. 9a, we can identify a robust falling trend of the long-term mean of MSLP over the polar region, which suggests a deepening trend of the Arctic low. Such a falling trend in DJF can also be reproduced by the numerical simulations in response to the reduction of Arctic sea ice (Higgins and Cassano 2009; Screen et al. 2014). As mentioned in Alexander et al. (2004), the reduction of Arctic sea ice increases the local surface heat fluxes, which in turn increases near-surface air temperature, enhances precipitation, and lowers the MSLP locally. Moreover, the stronger heat fluxes during a period of lower sea ice concentrations reduce the vertical static stability of the atmosphere (Jaiser et al. 2012). Because the atmospheric response to sea ice might depend on the mean state of the atmosphere, such as the Euro-Atlantic circulation (Balmaseda et al. 2010), we speculate that the stronger year-to-year variability of the UBI is related to the stronger atmospheric response of the extratropical...
Regression against the mean/variance trend of UBI of 20 GCMs (RCP8.5)

As can be seen in Fig. 9b, the long-term variance trend of MSLP is positive over the Barents, Kara, and Laptev Seas, and such a positive trend is robust over the UB sector. The underlying mechanisms linking the reduction of sea ice to the occurrence of UB is still unknown, and this is considered in our future work.
5. Implications of UB for the East Asian winter climate

A significant correlation between UBI and SHI, as well as their trends, was identified in section 4, suggesting that UB plays a crucial role in the mean state and interannual variation of the East Asian winter climate in the twenty-first century. Will the anomalous large-scale circulation features associated with UB strengthen or weaken on synoptic and seasonal time scales in response to increasing anthropogenic forcing? Because the anthropogenic forcing is strongest at the end of the twenty-first century, the analysis is performed for the period 2070–99 only.

a. Synoptic time scales

As in Part I, the development and mature stages are illustrated by the composites of Z500 and the 10-day high-pass filtered E vector at 250 hPa (Hoskins et al. 1983), whereas the mature and decay stages are...
demonstrated by the composites of MSLP tendencies and anomalies. The composite difference between the RCP runs and the HIST run is used to determine whether the large-scale circulation features are changed and whether the sign of these changes is the same in the majority of GCMs. Because the composite differences are comparable between the RCP4.5 run and the RCP8.5 run, differing mainly in magnitude only, we present only the results of the RCP8.5 run.

The large-scale circulation features in the RCP8.5 run are analogous to those in the HIST run (Figs. 6d–f of Part I). In the development and mature stages of UB, the momentum fluxes propagate eastward along the quasi-stationary Rossby wave train over the Atlantic and Eurasia (Figs. 10a–c). This is related to the eastward shift of an Atlantic storm track. The westerly momentum fluxes diverge from the Euro-Atlantic region and converge over the Ural Mountains. The convergence of the momentum flux over the Ural Mountains corresponds to deceleration of the westerly flow. This is essential for the build-up and maintenance of UB (Figs. 10b,c). In the meantime, the stronger meridional flow of UB enhances the northerly cold air advection from the polar region to western Siberia (downstream of UB). The SH undergoes intensification and the positive MSLP anomaly extends southeastward from the Urals toward the East Asian
coast (Figs. 11a–c). In the decay phase of UB, the break-
down of the SH and the migration of a cold surge can be
deduced by the negative MSLP tendencies over the Ural–
Siberia region and positive MSLP tendencies over the East
Asian continent (Figs. 11b,c). Apparently, the dynamics
linking UB and the SH do not show significant changes
under a warmer climate in the late twenty-first century.

Compared to the HIST run, the eastward propagation
of the momentum fluxes from the Euro-Atlantic region
becomes stronger in the majority of GCMs (Figs. 10d–f).
In the development stage, there are stronger momentum
fluxes traveling from Europe to the Urals (Fig. 10d).
This is likely due to changes in the background flow over
the Euro-Atlantic region, such as the intensification of
the eddy-driven jet over the North Atlantic (Fig. 8)
and the lower MSLP over the high-latitude region (Fig. 9a).
These changes are apparent in the MME differences be-
tween the RCP8.5 run and the HIST run, as can be inferred
from the change of U500 (Fig. 2f).

Associated with stronger momentum fluxes propa-
gating from Europe and converging near the Urals, the
positive MSLP anomalies over the Ural–Siberia region
appear to be stronger in the majority of GCMs, where
the larger MSLP anomalies have two local maxima
over the UB center and the SH (Fig. 11d). Besides
larger MSLP anomalies, the positive MSLP tendencies
are larger over the SH region, suggesting stronger in-
tensification of the SH (Fig. 11d). Following that, the

![Fig. 11. As in Fig. 10, but for MSLP anomalies (contours; hPa) and MSLP tendencies (shading; hPa day⁻¹) on days
0, 2, and 4 with respect to the UB onset. The zero contours are omitted and the negative contours are dashed.](image-url)
positive MSLP tendencies are larger over China, suggesting the stronger passage of a cold surge associated with the breakdown of the SH (Figs. 11e,f).

b. Seasonal time scale

On the seasonal time scale, the large-scale circulation features associated with UB are depicted by regression analysis, where the 30-yr DJF-mean time series of UBI is regressed against that of Z500 and MSLP for each of the 20 GCMs. The MMEs of the regression pattern of the HIST run and the RCP runs are shown in Fig. 12. The large-scale teleconnections of UB are comparable in the HIST run and the RCP runs (Figs. 12a–f). Corresponding to the more frequent occurrence of UB, the stronger high pressure system over the Urals can be inferred from the positive regression coefficients of both

Fig. 12. Regression of the UBI against the MSLP and Z500 (a),(b) in the HIST run for the period 1971–2000, and in the (c),(d) RCP4.5 and (e),(f) RCP8.5 runs for the period 2070–99. The zero regression coefficients are omitted, the negative contours are dashed, and the coefficients significant at the 95% confidence level are shaded. The contour interval is 0.2 hPa °1 for the MSLP and 2 gpm °1 for the Z500. The solid black box and dashed black box enclose the UB sector and the climatological SH region, respectively. In the left panel, the Tibetan Plateau is dark shaded.
MSLP and Z500 over the region (Figs. 12a–f). Upstream of UB, the regression coefficients of Z500 are negative near the Mediterranean Sea (10°–30°E; Figs. 12b,d,f). Downstream of UB, the regression coefficients of MSLP are positive in sign (Figs. 12a,c,e), and those of Z500 are negative in sign over the southern flank of the climatological SH region, suggesting a stronger baroclinicity over the East Asian winter monsoon region (Fig. 12b,d,f).

Such a teleconnection pattern is comparable to that associated with the dominant modes of the East Asian winter monsoon and UB (B. Wang et al. 2010; Sohn et al. 2011; Cheung et al. 2012).

Compared to the HIST run (Figs. 12a,b), the regression coefficients of the two RCP runs are larger in magnitude near the regression centers, and most of the significant regions expand (Figs. 12c–f). In particular, the positive regression coefficients of MSLP and Z500 over the Urals expand poleward to the Kara Sea and Laptev Sea. Wang and Chen (2014) also found a stronger relationship between the UBI and the MSLP and Z500 of the subpolar region. Their study showed that the recent strong East Asian winter monsoon epoch (2004–12) was characterized by pronounced Arctic warming and stronger high anomaly regions over the Kara Sea and Laptev Sea, where these characteristics could not be identified in the strong East Asian winter monsoon epoch (1976–87). Therefore, the difference in the regression patterns between the RCP runs and the HIST run might arise from the change in the atmospheric response over the extratropical region under Arctic warming, which needs to be further explored in future work.

6. Summary and discussion

In Part II of this study, we have projected the UB frequency and 30-yr running (long-term) mean and variance trends of UBI (Ural blocking index) and SHI (Siberian high intensity) in 20 CMIP5 GCMs in RCP4.5 and 8.5 runs. Our results show that UB still plays an important role in the East Asian winter climate on both synoptic and seasonal time scales in the late twenty-first century when anthropogenic forcing is strongest. An accurate projection of UB might be considered one of the crucial factors for the evaluation of future changes of the East Asian winter climate. The main findings of this study are summarized as follows:

- The MME of the UB frequency does not show a significant change in the twenty-first century in the two RCP runs, but a large spread is identified across the GCMs and is even larger in the RCP8.5 run. This suggests a larger uncertainty in the UB frequency under a mild climate, where the long-term variance of UBI tends to increase in the RCP8.5 run. The uncertainty might be related to a change in the atmospheric response of extratropical regions under climate change. This might also be related to the uncertainty of the central blocking longitude over Eurasia, which tends to shift eastward toward Asia associated with the eastward shift of the Atlantic storm tracks in a warmer climate (de Vries et al. 2013). The characteristics of blocking should also be assessed in future work.
- The long-term mean and variance trends of the UBI and the SHI (a proxy of the East Asian winter climate) across the GCMs are related. On one hand, the long-term mean trend of UBI might be related to the trend of the Atlantic jet stream. A significant negative trend of UBI is likely associated with a strengthening trend and a northeastward displacement of the Atlantic jet stream. On the other hand, the long-term variance trend of UBI might be related to the quasi-stationary Rossby wave train across Eurasia. The uncertainty of UBI seems to be related to how the climatological mean state over the Euro-Atlantic region will change.
- Based on these results, we also hypothesize that the uncertainty of UBI will cause uncertainty in the East Asian winter climate.
- The linkage between the long-term mean of UBI and the East Asian winter climate appears to be stable in the twenty-first century, but the large-scale circulation features associated with UB in the late twenty-first century might be different from those in the HIST period. On interannual time scales, regression analyses reveal that UB shows a significant correlation with the Z500 and MSLP over the Kara and Laptev Seas, where their correlations are weak in the HIST period. Indeed, the reduction of autumn Arctic sea ice in recent years has been linked to the warm Arctic–cold Siberia temperature pattern (Cohen et al. 2012). This also likely contributes to more frequent UB and more frequent cold winters in East Asia (Wu et al. 2011, 2013; Wang and Chen 2014). Therefore, the effect of Arctic sea ice on the UB frequency under a warmer climate is noteworthy.
- The underlying dynamics of UB do not have notable changes in the late century. The formation and maintenance of UB is related to the eastward shift of an Atlantic storm track. The associated momentum fluxes converge near the Ural Mountains result in deceleration of the westerly flow over there. However, because of apparent changes of the large-scale circulation over the Euro-Atlantic region, such eastward propagating momentum fluxes appear to be stronger and these result in a stronger intensification of UB. Then, UB might exert a stronger impact on the
synoptic evolution of SH and the cold air outbreak in East Asia.

Although the uncertainty of UB and its possible cause in the CMIP5 GCMs have been identified in this study, the underlying mechanism of the uncertainty is not yet fully understood. A better understanding of the cause of the uncertainty could be gained by performing numerical experiments and focusing on the atmospheric response of the extratropical circulations to the sea surface temperature and the Arctic sea ice. On one hand, recent studies have demonstrated that an accurate representation of sea surface temperature conditions over the Atlantic is crucial for model simulations of blocking frequency over Eurasia (Scaife et al. 2011), the North Atlantic storm track (Woollings et al. 2012), and the troposphere–stratosphere interaction (Omrani et al. 2014). On the other hand, Francis and Vavrus (2012) hypothesized that Arctic warming results in the slowing of Rossby wave propagation and a higher amplitude flow in the midlatitudes. However, linkage between Arctic warming and blocking is not robust in the observational reanalysis datasets and CMIP5 models (Woollings et al. 2014). We suggest that future work should diagnose the role of sea surface temperature over the Atlantic and the Arctic sea ice in the formation and maintenance of blocking.

Acknowledgments. The first author is a recipient of a research studentship provided by the City University of Hong Kong (CityU). This study is partly supported by National Nature Science Foundation of China Grants 41375096 and 41175079, and CityU Strategic Research Grant 7004004. Last but not least, we greatly appreciate the critical and detailed comments provided by the three anonymous reviewers.

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