Implications of Ural Blocking for East Asian Winter Climate in CMIP5
GCMs. Part I: Biases in the Historical Scenario

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Abstract

This study assesses the ability of the 25 GCMs from phase 5 of the Coupled Model Intercomparison Project (CMIP5) to simulate Ural blocking (UB) and its linkage with the East Asian winter climate [December–February (DJF)] in a historical run (1950/51–2004/05). A Ural blocking index (UBI) is defined as the DJF-mean blocking frequency over 45°–90°E for each winter.

Regression analyses suggest that the long-term mean bias of UBI is caused by the long-term mean circulation bias over the North Atlantic. On seasonal time scales, the GCMs simulating a positive bias of UBI are associated with a stronger Atlantic jet stream, as well as stronger westerly momentum fluxes from the North Atlantic to Europe. On synoptic time scales, however, these GCMs tend to be associated with a weaker Siberian high and East Asian trough during the evolution of a UB event. Altogether, there is no apparent linkage between the long-term mean bias of UB and the East Asian winter climate. Further studies are needed to explore the teleconnection between UB and the East Asian winter climate in the GCMs.

1. Introduction

Atmospheric blocking (‘‘blocking’’) refers to the persistence of a quasi-stationary high pressure system over the extratropics. It exhibits a reversal of the meridional pressure gradient, persistently interrupts the midlatitude westerlies, and often brings widespread extreme weather (e.g., Trigo et al. 2004; Buehler et al. 2011). Recent examples include the severe snowstorm in southern China in 2008 (Tao and Wei 2008; Zhou et al. 2009) and the Russian heat wave and the Pakistan flooding in 2010 (Lau and Kim 2012). Extensive work is still needed to improve the poor performance of general circulation models (GCMs) in simulating blocking occurrence and maintenance (e.g., Matsueda et al. 2009; Scaife et al. 2010; Anstey et al. 2013; Masato et al. 2013). In this study, we focus on the wintertime blocking near the Ural Mountains [called Ural blocking (UB) in the literature], which is known as the third frequency peak in the Northern Hemisphere (Shukla and Mo 1983; Diao et al. 2006). The assessment of blocking over this region has received less attention compared to two climatological regions, the Euro-Atlantic sector and the Pacific sector (e.g., Barriopedro et al. 2006; Davini et al. 2012).

In boreal winter, the occurrence of UB persistently enhances the southward cold advection downstream and reinforces the Siberian high (SH; Cheung et al. 2013b). The SH is a prominent cold-core anticyclonic system near the surface, which is known as one of the semi-permanent features of the East Asian winter climate (e.g., Ding 1994; Chang et al. 2006). When UB decays, the strengthened SH breaks down and triggers a severe cold air outbreak in East Asia (Tao 1957; Cheung et al. 2013b). This may bring intense cold air masses to densely populated areas of the East Asian continent. If UB persists or recurs for a prolonged period, it may trigger extremely long-lasting cold weather in the region, such as the severe snowstorm in southern China as mentioned previously. On seasonal time scales, a strong year-to-year correlation exists between the wintertime UB frequency and the Siberian high intensity (SHI; L. Wang et al. 2010; Cheung et al. 2012). Between the early 1960s and the early 2000s, the significant decreasing trend of the UB frequency likely contributed to a weakening tendency of the East Asian winter climate and a decline of cold extremes in China (L. Wang et al. 2010; Wei et al. 2011; Yan et al. 2011).
Because of the strong observed link between UB and the SH on synoptic and seasonal time scales, UB is one of the important factors that has to be evaluated when looking at future East Asian winter climate. Many studies have assessed blocking over the Northern Hemisphere (e.g., D’Andrea et al. 1998; Barriopedro et al. 2010; Barnes et al. 2012; Anstey et al. 2013; Dunn-Sigouin and Son 2013; Masato et al. 2013) and in the East Asian winter climate (e.g., Ji et al. 1997; Hu et al. 2000; Hori and Ueda 2006; Sohn et al. 2011; Wei et al. 2014; Gong et al. 2014). However, none of these studies evaluates model performance in simulating UB and its linkage with the East Asian winter climate. Recently, the state-of-the-art GCMs from phase 5 of the Coupled Model Intercomparison Project (CMIP5) have been widely used for evaluating both global and regional climate under different emission scenarios on a daily basis (Taylor et al. 2012). In this study, analyses are confined to 25 CMIP5 GCMs and are divided into two parts [Part I (this paper) and Part II (Cheung and Zhou 2015, hereinafter Part II)], with an emphasis on present and future climate conditions (Table 1).

In Part I, we present the results of the historical scenario. The main goal is to assess the ability of the 25 CMIP5 GCMs to simulate UB and its linkage with the East Asian winter climate. Moreover, the biases of UB are identified and their role in the biases of the East Asian winter climate is investigated. The assessment is achieved by comparing the results with the NCEP–NCAR reanalysis datasets. Throughout the analyses, we attempt to answer the following questions:

1) How well do CMIP5 GCMs reproduce the climatological features of wintertime Ural blocking?
2) What are the possible causes of the biases of UB in the CMIP5 GCMs?
3) Do the biases of UB affect the East Asian winter climate in the CMIP5 GCMs?

Overall, this paper is organized as follows: The data and methods are presented in section 2. Section 3 describes how well the CMIP5 GCMs measure the statistics of UB. Section 4 focuses on the cause of the biases of UB. Section 5 determines whether the biases of UB cause any changes in the East Asian winter circulation. Finally, the biases of UB and their implications for the East Asian winter climate are discussed and concluded in section 6.

### 2. Data and methods

#### a. Data and terminology

The study period covers the 55 years from 1950/51 to 2004/05, and the winter covers the three consecutive

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**Table 1. Description of 25 CMIP5 GCMs used in this study, where the letters V and X represent whether the data was (V) or was not (X) available for a specific scenario. Expansions of institutions and model names are available online at http://www.ametsoc.org/PubsAcronymList.**

<table>
<thead>
<tr>
<th>Code</th>
<th>Institution, country</th>
<th>Model</th>
<th>Horizontal resolution (lat × lon)</th>
<th>Scenario</th>
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<td>V</td>
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<td>CanESM2</td>
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<td>V</td>
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<td>NOR</td>
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<td>NorESM1-M</td>
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<td>V</td>
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months from December through February (DJF). For example, winter 1950 refers to the 3-month period from December 1950 to February 1951. The raw data include the NCEP data (NCEP–NCAR reanalysis datasets) and the output of 25 CMIP5 GCMs. For the CMIP5 data, we extracted the first ensemble member (r1i1p1) of the GCMs from the Earth System Grid Federation data portal (http://pcmdi9.llnl.gov/esgf-web-fe/), as listed in Table 1. Before we carried out analyses, we bilinearly interpolated the CMIP5 data into a horizontal resolution of 2.5° latitude × 2.5° longitude, which is the same as the NCEP data.

In our analyses, the daily and DJF (winter) climatology is obtained using the data from the 55-yr study period. In particular, the daily climatological mean is determined by a 31-day running mean (i.e., a monthly cycle including 15 days before and after each calendar day). The multiple model ensemble (MME) is taken as simply the unweighted average of all listed GCMs. The term bias is used to describe the departure of a quantity in the CMIP5 GCMs from that in the NCEP.

b. Blocking detection algorithm

Atmospheric blocking is detected by applying zonal index equations (e.g., Tibaldi and Molteni 1990) to the daily field of the 500-hPa geopotential height (Z500). Five major steps are included to extract the blocking events and frequencies in the Northern Hemisphere.

1) ZONAL INDEX

To begin with, the two zonal index equations (ZIN and ZIS), Eqs. (1) and (2), are used to determine whether the flow over a longitude is zonal or meridional. In all calendar days $t$, ZIN and ZIS are obtained for each longitude ($\lambda$):

$$
\text{ZIN}(\lambda, \phi_0, t) = \left\{ \begin{array}{ll}
0 & \text{if } \text{ZIN}(\lambda, \phi_0, t) > -10 \\
1 & \text{if } \text{ZIN}(\lambda, \phi_0, t) \leq -10 \\
\end{array} \right.
$$

$$
\text{ZIS}(\lambda, \phi_0, t) = \left\{ \begin{array}{ll}
0 & \text{if } \text{ZIS}(\lambda, \phi_0, t) < 0 \\
1 & \text{if } \text{ZIS}(\lambda, \phi_0, t) \geq 0 \\
\end{array} \right.
$$

where

$$
t \in [1 \text{ Jan 1950, 31 Dec 2005}],
$$

$$
\lambda \in [0, 357.5]°E,
$$

$$
\phi_N = 80°N + \Delta,
$$

$$
\phi_0 = 60°N + \Delta,
$$

$$
\phi_S = 40°N + \Delta,
$$

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

The blocking-type circulation is characterized by the reversal of the daily meridional Z500 gradients at the extratropical region, which is defined as ZIN $\leq -10$ gpm ($°$ latitude)$^{-1}$ and ZIS $\geq 0$, as in Barriopedro et al. (2006):

2) BLOCKING LONGITUDE

A longitude is considered blocked [blocking longitude (BL)] if ZI = 1 for at least one of the five delta values, that is,

$$
\text{BL}(\lambda, t) = \max[ZI(\lambda, \phi_0, t)]
$$

3) BLOCKING REGION/LARGE-SCALE BLOCKING

Because blocking is a large-scale system, its spatial scale should be greater than the Rossby radius of deformation, which is around 1000 km. For large-scale blocking, called a blocking region (BR), the minimum extension (size) is set at 12.5° longitude (i.e., $\text{BL} = 1$ for five consecutive $\lambda$). When a BR is identified, the western and eastern boundaries of the BR are considered the upstream and downstream longitudes ($\lambda_{up}$ and $\lambda_{down}$) and the distance between them is the extension. Moreover, the center of a BR ($\lambda_{ctr}$, $\phi_{ctr}$) is defined as the grid with the largest positive Z500 anomaly within the BR.

4) BLOCKING EVENT

The tracking procedure is implemented to decide which of the BRs belong to the same blocking event. This method is similar to the algorithm of Barriopedro et al. (2006). First, on a calendar day $t$, if the centers of any two or more BRs are closer than 45° longitude, these BRs are considered to be the same blocking event. Second, if (i) a BR on day $t$ overlaps with another BR on day $t + 1$ (i.e., at least one $\lambda$ is a BL in the two BRs), or (ii) the distance between the centers of these two BRs is less than 20° longitude, then the two BRs are also considered to be the same blocking event.
After tracking all BRs, the profile of each of the blocking events is recorded:

• $t_i$ and $t_f$: the time at the first and final date, which is regarded as the establishment and decay of a blocking event;
• $\lambda_i$ and $\lambda_f$: the center longitude position at the first and final date;
• duration: the lifespan, which is the number of days between $t_i$ and $t_f$.

5) BLOCKING FREQUENCY

Considering the characteristic time of the blocking region, the duration of all blocking events under investigation should be at least four consecutive days (Pelly and Hoskins 2003). The blocking frequency at each longitude of a month (say, January 1950) is counted as the number of days in which a blocking event (duration $\geq 4$ days) can be identified over that longitude throughout that month:

Monthly blocking frequency $= BF(\lambda, yr, month)$, \hspace{1cm} (3)

where $yr \in [1950, 2005]$ and month $\in [1, 12]$.

c. Ural blocking

To qualitatively analyze the cause and effect of the bias of Ural blocking on synoptic and seasonal time scales, we extract the blocking events and frequencies over 45°–90°E from the blocking algorithm, where the boundary is consistent with that of other studies of this sector blocking (e.g., L. Wang et al. 2010; Cheung et al. 2012, 2013a).

UB events refer to those blocking events lasting for at least four calendar days, and those events must be centered over 45°–90°E when they establish (i.e., $\lambda_i \in [45°, 90°]E$) and the onset date ($t_i$) should be in the DJF period [see section 2b(4)]. It should be noticed that the UB events tend to move eastward (Cheung et al. 2012);

The Ural blocking index (UBI), on the other hand, is defined as the DJF-mean blocking frequency over 45°–90°E for each winter, that is, $UBI(yr)$, where $yr \in [1950, 2004]$ [see section 2b(5), Eq. (3)]. The long-term mean and variance of UBI are determined by the 55-yr time series of UBI.

d. Siberian high intensity

The implication of UB for the East Asian winter climate is due to the Siberian high intensity, which is closely related to cold air activity over East Asia (e.g., Ding 1994; Chang et al. 2006; Zhou et al. 2007; L. Wang et al. 2010). The SHI is taken as the normalized mean sea level pressure (MSLP) over the climatological region of the cold-core high (40°–65°N, 80°–120°E) (Panagiotopoulou et al. 2005). The daily and DJF-mean SHI index is normalized by the daily and DJF-mean climatology as described in section 2a.

3. Climatological statistics of Ural blocking

a. Frequency of occurrence

The winter climatology of the blocking frequency over the Northern Hemisphere is shown in Fig. 1, where the
results of the NCEP are consistent with the ERA-40 reanalysis datasets (not shown). Most of the CMIP5 GCMs are able to reproduce the two climatological peaks over the Euro-Atlantic sector and the Pacific sector. However, they often significantly underestimate the blocking frequency in the former region, and their biases diverge over the Ural and Pacific sectors. The biases are consistent with similar studies that use other blocking detection methods (Anstey et al. 2013; Dunn-Sigouin and Son 2013; Masato et al. 2013), as well as earlier generations of GCMs [D’Andrea et al. 1998; Parry et al. 2007 (see their section 8.4.5); Barriopedro et al. 2010; Barnes et al. 2012]. Apart from the results of the aforementioned studies, we need to understand why the UB frequency spread across different GCMs.

Because the climatological UB frequency diverges across different GCMs, we wonder whether such a difference could be attributed to any biases of large-scale circulation in the GCMs, which is investigated in section 4. To further investigate the discrepancy of the UB frequency across the 25 CMIP5 GCMs, the boxplot of UBI is illustrated in Fig. 2a, where on the x axis the GCMs are ranked in ascending order by the long-term mean of UBI. The y axis of the boxplot shows the 10th, 25th, 50th, 75th, and 90th percentiles of the quantity (see the diagram on the right of Fig. 2), where the percentiles are obtained by extrapolation.

The long-term mean of UBI shows a slightly negative bias and its 90th percentile shows a stronger negative bias. With a two-tailed Student’s t test, the long-term mean of UBI is shown to be positively (negatively) biased in 3 (11) GCMs, where it is significantly larger (smaller) than the NCEP at the 95% confidence level (Table 2). These GCMs are denoted by blue (red) markers in Fig. 2 and are called UBI$_1$ (UBI$_2$) GCMs hereafter. The remaining UBI$_{\text{NORM}}$ GCMs (no significant difference) are denoted by black markers.

b. Duration

In addition to the blocking frequency, the impact of UB on East Asian winter circulation is attributed to individual events on synoptic time scales. Accordingly, we compare the duration of UB events in the CMIP5 GCMs with the NCEP, as shown in Fig. 2b. As can be inferred from Fig. 2a, all UBI$_1$ GCMs are able to simulate a high winter-mean UB frequency, since they have a larger mean and 90th percentile UBI than the NCEP. When the 90th percentile of duration is compared in Fig. 2b, the MME seems to be comparable to that of the NCEP. However, it is noticeable that not all of these GCMs can reproduce UB events as long-lived as those of the NCEP. Many UBI$_1$ GCMs and one of the UBI$_2$ GCMs are also deficient in simulating UB events of such a long duration. Indeed, this deficit has also been reported in other numerical studies for the Euro-Atlantic sector, but not for the Pacific sector (e.g., Tibaldi et al. 1997; Barriopedro et al. 2010; Dunn-Sigouin and Son 2013). In other words, there are different causes for the bias of the frequency and the duration of UB events. The possible causes and effects of these biases are deduced by comparing the circulation pattern associated with UB in the CMIP5 GCMs with that in the NCEP.

4. Cause of biases of UB occurrence

a. Biases of long-term mean circulation

The long-term mean biases of large-scale circulation are highlighted by the winter climatology of MSLP, Z500, and 250-hPa zonal wind (U250) in the MME and the NCEP data (Figs. 3a–c), as well as the climatological differences between the MME and NCEP (Figs. 3d–f). The MSLP difference gives rise to a tripole pattern consisting of an anomalous high pressure along the subtropics, an anomalous low pressure over Europe, and another anomalous high pressure over the subpolar region in Eurasia (Fig. 3d). Over Europe, the southward shift of the low is associated with a stronger trough and enhanced midlatitude westerlies (Figs. 3e,f). This is consistent with previous studies that suggested a linkage...
between the strength of the Atlantic jet stream and the long-term mean bias of the Euro-Atlantic blocking frequency in GCMs (e.g., Barriopedro et al. 2010; Barnes et al. 2012; Barnes and Polvani 2013; Davini and Cagnazzo 2013). Associated with stronger midlatitude westerlies over Europe, the Euro-Atlantic blocking tends to shift eastward such that the blocking frequency over Europe decreases (de Vries et al. 2013). This is probably why the secondary blocking frequency peak becomes more pronounced near the Ural Mountains (60°E) when the Euro-Atlantic blocking is significantly underestimated in the MME (see Fig. 1 in section 3a).

When the long-term mean of UBI is regressed against that of MSLP and Z500 across the 25 CMIP5 GCMs, we obtain a statistically significant signal over the Euro-Atlantic region (Figs. 4a,b). Specifically, the regression pattern consists of a dipole with the positive center of action is located northwest of the Iberian Peninsula (45°N, 20°W) and the negative center of action is located northwest of Iceland (70°N, 25°W; Figs. 4a,b). The centers of action are close to the Azores high and the Icelandic low (Fig. 3a). The above result suggests a stronger climatological meridional pressure gradient over the North Atlantic associated with the positive bias of the UBI. Associated with a stronger meridional pressure gradient (Figs. 4a,b), the eddy-driven jet over the Atlantic likely becomes stronger and tends to move northeastward (Fig. 4c). This bias seems to be similar to that of European blocking, which is related to the speed of the Atlantic jet stream (Barnes and Polvani 2013). Moreover, this bias seems to contribute to weaker U250 over the Urals and a positive bias of UBI. The above results suggest that the long-term mean bias of UBI is linked to that of the Euro-Atlantic circulation, such as the position and strength of the Atlantic jet stream.

On the other hand, the MSLP has a positive bias over the Barents and Kara Seas (70°–80°N, 30°–90°E; Fig. 3d). Observational studies have suggested that an above-normal MSLP centered near this region likely accompanies less cyclone activity traveling poleward to the Arctic (Rogers and Thompson 1995; Thompson and Wallace 1998). In the meantime, there is more cyclone activity moving eastward from the Euro-Atlantic region across the midlatitudes in Europe (Rogers and Thompson 1995; Thompson and Wallace 1998). This excessive zonal cyclone activity is also evidenced by the negative MSLP bias along the midlatitudes in Europe (Fig. 3d). This suggests the role of transient eddies in the bias of UB

### Table 2. Climatological means of the UBI (unit: days) in the 25 CMIP5 GCMs arranged in ascending order. The colors and acronyms are used in the figures. The p value shows the significance level based on the two-tailed Student’s t test between the long-term mean UBI of an individual GCM and that of the NCEP.

<table>
<thead>
<tr>
<th>No.</th>
<th>Color</th>
<th>Acronym</th>
<th>Model/data</th>
<th>UBI (mean ± SD)</th>
<th>p value</th>
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<tbody>
<tr>
<td>1</td>
<td>Red</td>
<td>FGO</td>
<td>FGOALS-g2</td>
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<td>3</td>
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<td>3.05 ± 2.77</td>
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<tr>
<td>4</td>
<td>Red</td>
<td>M13</td>
<td>MIROC-ESM-CHEM</td>
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<tr>
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besides the low-frequency circulation over the Euro-Atlantic region.

b. Biases of transient eddies

The role of transient eddies can be depicted by the $E$ vector ($\bar{u}'^2 - u't'$) proposed by Hoskins et al. (1983), where the overbar denotes the time averaged quantity and the prime denotes a deviation from this average. Applying the Lanczos filter with 31 weights (15 days before and after a calendar day) and a cutoff frequency at 10 days for all DJF days between 1950 and 2004, the climatology of the high-pass $E$ vector at 250 hPa and the high-pass poleward heat flux ($\bar{u'}T'$) at 700 hPa in NCEP and the MME is illustrated in Figs. 5a and 5b. In particular, the divergence and convergence of the $E$ vector measures the acceleration and deceleration of the mean westerlies due to the transient eddies. The heat flux provides a more complete picture of the eddy structure at the lower troposphere.

Compared to NCEP, the transient eddies of the MME are weaker over the western Atlantic, with biases in the easterly momentum flux and negative heat flux (Fig. 5c). Moreover, the transient eddies are enhanced over the European continent, with biases in the westerly momentum flux and positive heat flux (Fig. 5c). The above biases over the Euro-Atlantic region agree with the
positive bias of the storm track density, as shown in Fig. 3c of Zappa et al. (2013). The bias of the Atlantic storm track has been shown to be related to that of wintertime European blocking (Zappa et al. 2014). We will demonstrate that this bias is also related to UB.

As shown in Fig. 5d, when the $E$ vector and the poleward heat flux are regressed against the UBI across the 25 CMIP5 GCMs, the divergence of momentum flux and the heat flux are stronger near the exit region of the climatological storm track over the Atlantic. In contrast, a stronger convergence of momentum flux and a weaker heat flux can be identified near the Urals. The negative bias of westerlies over the Urals, which leads to the positive bias of UBI, appears to be related to the positive bias of transient eddies over the Atlantic.

Because we have shown that the bias of UBI is related to the MSLP dipole pattern centered near Iceland and the Iberian Peninsula (Fig. 4a), we speculate that this bias is related to the bias of the North Atlantic Oscillation (NAO), which is the dominant mode of climate variability over the North Atlantic (Wallace and Gutzler 1981; Barnston and Livezey 1987). The NAO is obtained by the first rotated empirical orthogonal functions of monthly geopotential height anomalies at 700 hPa (Z700) north of 20°N using the NCEP data (Barnston and Livezey 1987). Then, the monthly NAO index (NAOI) of a GCM is acquired by projecting the eigenvector of the NCEP data onto the monthly Z700 anomalies of the GCM. Afterward, the winter climatology of the NAOI of each GCM is taken as the DJF-mean NAOI for the period 1950/51–2004/05.

The long-term mean of $E$ vector and the poleward heat flux is regressed against the NAOI across the GCMs (Fig. 5e). Compared to Fig. 5d, the energetics associated with the NAOI also corresponds to an enhanced heat flux and a stronger divergence of momentum flux near the exit region of the Atlantic storm track. When a partial regression is carried out for UBI and the large-scale circulation parameters in Fig. 4 by removing the covariance of UBI and NAOI, no prominent signals can be identified over the Euro-Atlantic region (not shown). On the other hand, the regression pattern associated with the NAOI gives rise to a stronger southward instead of an eastward component of the momentum flux. Accordingly, the convergence of the momentum flux associated with the NAOI corresponds to the meridional displacement of the jet, whereas that associated with UB corresponds to the eastward extension of the jet. The bias of transient eddies associated with the bias of NAOI only partially explains the bias of UB occurrence in the 25 CMIP5 GCMs.

In addition to the NAOI, there should be other factors altering the eastward propagation of transient eddies from the Atlantic to Eurasia and its convergence over the Ural–Siberia region, which in turn affects the occurrence of UB in a GCM. These might be partly due to the biases of stationary eddies and their interaction with transient eddies. However, when the long-term mean
bias of UBI is regressed onto the low-pass (>10 days) E vector and the low-pass filtered wave activity flux postulated by Takaya and Nakamura (2001), no prominent signals can be found over the Urals and Siberia (not shown). The signal is also not pronounced when the low-pass E vector is replaced by the interaction term of the E vector. Therefore, the cause of bias of UB should be further investigated in future work.

5. Do UB biases have any implication for the East Asian winter climate?

As shown in section 4b, the winter climatological transient eddies of the MME have an eastward shift from the Atlantic basin toward the Eurasian continent. Based on this finding, it is important to figure out whether there is any bias of transient eddies during the evolution of UB events, and whether such a bias is related to that of UBI. Moreover, the Siberian high, the prominent near-surface feature of the East Asian winter climate, is slightly weaker in the CMIP5 GCMs [see Fig. 3d in section 4a; see also Fig. 3a of Gong et al. (2014)]. Because of the crucial linkage between UB and the SH, as mentioned in introduction, it is also important to understand whether the deficiency of a GCM in simulating UB and the East Asian winter climate is related.

To depict the transient eddies and the large-scale circulation in the life cycle of UB events, we show the E vector and the Z500 anomalies in the development and mature stage of UB events (Fig. 6). Note that the Z500 anomalies are representative of the synoptic-scale features of UB, since the tropospheric circulation resemble an equivalent barotropic structure upstream and near the center of UB (not shown).

The large-scale circulation features of the NCEP reanalysis data resemble a quasi-stationary Rossby wave train over Eurasia (Figs. 6a–c). Near the upstream low of UB, the momentum flux is divided into two branches, where one diverges from UB and propagates toward East Asia and the North Pacific over the midlatitudes, and one travels along the subtropical region. This is related to the eastward extension of the Atlantic storm

Fig. 5. The 55-yr climatology of the high-pass E vector at the 250-hPa (vector; m² s⁻²) and the high-pass poleward heat flux at 700 hPa (shading; K m s⁻¹) for (a) NCEP and (b) the MME, and (c) their composite difference. Also shown is regression of the E vector and the heat flux against (d) the UBI (vector; m² s⁻² %⁻¹; shading; K m s⁻¹ %⁻¹) and (e) the NAOI (vector; m² s⁻²; shading; K m s⁻¹) across the 25 GCMs. In (c)–(e), vector and shading are significant at the 95% confidence level.
track associated with the formation of UB (Luo 2005; Luo et al. 2010; Cheung et al. 2013b). Compared to the NCEP, the Z500 anomalies of the MME look like an annular dipole (Figs. 6d–f). The upstream low anomaly over Europe is weaker and it is displaced southeastward toward the Mediterranean Sea. This corresponds to a stronger momentum flux propagating southward from the Euro-Atlantic region. On the other hand, the northern branch of the momentum flux appears to be convected mostly near UB and its downward propagation from the Urals to East Asia is much weaker. As a result, the MME does not well reproduce the large-scale circulation features and the underlying dynamics associated with UB. The results also suggest the deficiency of the MME to simulate the downstream impact of UB on the East Asian winter climate.

To further illustrate the linkage between UB and the East Asian winter climate in the GCMs, the daily time series of SHI throughout the evolution of UB is shown in Fig. 7. Based on observational analyses, the cold air outbreak in East Asia is characterized by the breakdown of the SH. This is preceded by an upper-tropospheric short-wave trough together with the polar jet propagating eastward over western Siberia ahead of an upstream ridge (Wu and Chan 1997). Because of weaker momentum fluxes propagating eastward from the Urals to East Asia (Fig. 6), the MME does not well reproduce

![Fig. 6. Composite maps of the Z500 anomalies (shading; gpm) and the high-pass E vector the 250-hPa (vector; m²s⁻²) on days -2, 0, and 2 with respect to the UB onset in (left) NCEP and (right) MME. The purple box encloses the climatological SH region.](http://journals.ametsoc.org/jcli/article-pdf/28/6/2203/4053632/jcli-d-14-00308_1.pdf)

![Fig. 7. Daily Siberian high index (SHI) during the evolution of UB, showing the (a) spread and (b) value of the 25 CMIP5 GCMs. Unit: hPa.](http://journals.ametsoc.org/jcli/article-pdf/28/6/2203/4053632/jcli-d-14-00308_1.pdf)
East Asia are weaker (Fig. 8b). Both the East Asian trough and the SH appear to shift northward, as evidenced by the negative Z500 regression coefficients to the north of 45°N and the negative MSLP regression coefficients at the northwestern boundary of the climatological SH region, respectively. The northward shift of these systems suggests weaker East Asian winter monsoon activities (Chen et al. 2000, 2005; B. Wang et al. 2010). As a result, the impact of a UB event on the East Asian winter climate is weaker for the UBI* GCMs than the UBI2 GCMs.

Although the UBI* GCMs simulate a higher UB frequency than the UBI2 GCMs, they tend to show a weaker SH reinforcement during a UB event (Figs. 7 and 8). Based on these results, it is unclear if UB of the UBI* GCMs or UBI2 GCMs exerts a stronger impact on the East Asian winter climate on seasonal time scales. To deduce such an impact, we multiple the daily SHI in Fig. 7b by the number of UB events per winter for each GCM (Fig. 9). This product represents the time of the East Asian winter climate is influenced by UB. If this product is larger in a GCM, then UB of this GCM exerts a stronger impact on the East Asian winter climate via the SH reinforcement, and vice versa.

As shown in Fig. 9, this product tends to be smaller in the UBI2 GCMs, suggesting the lower SHI of these GCMs due to the lower occurrence of UB. However, the product is comparable between UBI* GCMs and UBI2 GCMs. The above results do not provide evidence for the strong linkage between the bias of UB and the East Asian winter climate on seasonal time scales. These results appear to be consistent with the insignificant correlation between the bias of UB and that of East Asian winter circulation across the GCMs (see Fig. 4 in section 4a). Because we showed that the bias of UB is partly related to the NAOI, we will analyze the large-scale teleconnection of UB and its relationship with the East Asian winter climate in the GCMs in our future works.

6. Discussion and conclusions

According to previous observational studies, UB not only acts as an important precursor of extreme cold spells in East Asia (Tao 1957; Takaya and Nakamura 2005; Tao and Wei 2008; Lu and Chang 2009; Zhou et al. 2009), but also affects the strength of the East Asian winter climate (L. Wang et al. 2010; Cheung et al. 2012; Liu et al. 2014). As shown in Cheung et al. (2012), more frequent occurrence of UB is associated with a stronger ridge–trough couplet over the Asian continent and a stronger SH, and vice versa. Thus, it is important to study the strengths and weaknesses of the CMIP5 GCMs in simulating UB and its impact on the East Asian winter climate. Specifically, the focus of this study is to identify the possible causes and effects of the biases related to UB.

a. Causes of biases

Compared to the NCEP, the simulated Z500 is lower and the midlatitude westerly jet of the MME is usually stronger. In addition to a stronger midlatitude westerly flow over the North Atlantic, the storm track tends to shift eastward toward the European continent. Accordingly, the blocking frequency shows an eastward shift over the Eurasian continent, which has been demonstrated by Luo (2005), Luo et al. (2010), and de Vries et al. (2013).

Across the CMIP5 GCMs, the long-term mean bias of UB occurrence is closely related to that of the large-scale circulation over the North Atlantic. When the Atlantic jet stream in a GCM gets stronger, it tends to shift northeastward and is accompanied by stronger transient eddies over Europe. Associated with a stronger convergence of transient eddies near the Urals, the
zonal wind gets weaker near the Urals, and this corresponds to the positive bias of UBI. In particular, the source of bias of transient eddies is related to the climatological mean state over the North Atlantic. Further work is required to analyze the role of sea surface temperature over the Atlantic in causing the bias of UB, and to explore the physical cause of the convergence of transient eddies near the Urals.

b. Effects of biases

On synoptic time scales, the development of UB is accompanied by an eastward propagation of transient eddies from the Atlantic to Asia, and this also reinforces the SH. However, the CMIP5 GCMs do not well simulate the upstream signals over the Euro-Atlantic region. They are deficient in simulating the propagation of transient eddies from UB to East Asia. Consequently, the GCMs are able to simulate the reinforcement of SH during the development stage of UB, but they fail to capture the downstream impact of UB on East Asian winter circulation in the decay stage of UB.

While the CMIP5 GCMs simulating the positive bias of UBI are related to the positive bias of NAOI on a seasonal time scale, these GCMs are likely associated with stronger transient eddies over Europe during the evolution of UB events. However, the bias of synoptic transient eddies converges upstream of the Urals, which is accompanied by a weaker upstream trough of UB. Associated with the positive bias of UBI, the SH tends to be weaker and shifts northwestward, whereas the East Asian trough tends to shift northward. These circulation anomalies correspond to weaker winter monsoon activities over East Asia (Chen et al. 2000, 2005; B. Wang et al. 2010), which might be due to stronger zonal flow associated with the positive bias of NAOI. As a result, the positive bias of NAOI might enhance the wintertime UB occurrence, but this might correspond to a weaker SH reinforcement. These results lead to a weak impact of the long-term mean bias of UBI on the East Asian winter climate across the CMIP5 GCMs.

The other possible reason for the weak linkage between these biases is that a UB event usually lasts for several days (the 90th percentile of duration is less than two weeks; see Fig. 2b). Unlike sea surface temperature and snow cover, UB bias rarely exerts a persistent forcing on the East Asian circulation throughout a winter period. The long-term biases of the East Asian winter climate, such as a stronger and deeper East Asian trough, may also be caused by other model biases. This will definitely require more work that focuses on the East Asian winter climate, but it is outside the scope of the present study.

c. Conclusions

In Part I of this study, we have attempted to identify the biases of UB and to assess their impact on the East Asian winter climate in the historical scenario of 25 CMIP5 GCMs compared to the NCEP reanalysis data. The biases are partly related to the mean circulation bias over the North Atlantic. Although the CMIP5 GCMs are able to simulate the reinforcement of SH during the development stage of UB, they do not well reproduce the breakdown of SH in the decay stage of UB. This suggests the inability of the GCMs to simulate the underlying dynamics of UB and their impact on the East Asian winter climate. The relationship between UB and the East Asian winter climate in the GCMs should be analyzed by future works since it is important for evaluating the impact of blocking on the regional climate.

As a result of increasing greenhouse gas concentrations in the atmosphere, the surface air temperature is very likely to increase systematically in the twenty-first century (Parry et al. 2007). Because the land warms at a faster rate than the ocean, the land–sea thermal contrast is expected to decrease, and this will be accompanied by a weaker East Asian winter monsoon (EAWM). We wonder if the change of UB would be linked to those of the EAWM. In Part II of this study, we will project the UB frequency in both RCP 4.5 and RCP 8.5 scenarios. We will examine the uncertainty of the UB frequency based on its spread in the two RCP scenarios, and how the uncertainty might present a challenge for evaluating the East Asian winter climate.

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