Simulation and Projection of Blocking Highs in Key Regions of Eurasia by CMIP5 Models

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Abstract

It has been argued that the Coupled Model Intercomparison Project phase 5 (CMIP5) models underestimate the frequency of atmospheric blocking, while projecting a decreasing trend of blocking in the 21st century in the Northern Hemisphere. This average trend may not be true for regional blockings. Focusing on three key regions in Eurasia (the Urals, Baikal, and Okhotsk regions) where blocking significantly influences the weather and climate of East Asia, this study first evaluates the performance of the CMIP5 models by comparing historical simulations with National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (NNR). Possible changes in the first half of the 21st century are then analyzed using the RCP4.5 and RCP8.5 experiments. It is found that instantaneous blocking frequencies are underestimated in the Urals and Baikal regions for the whole year and in the Okhotsk region in summertime but are overestimated in Okhotsk in wintertime. Blocking episode frequency in the Urals and Baikal regions is underestimated by most of the 13 CMIP5 models, especially the short-duration blocking episodes (4–5 days), and the simulations are better in wintertime than in summertime. However, in the Okhotsk region, the modeled frequency of blocking episodes
1. Introduction

Atmospheric blocking is a dynamic phenomenon in the extratropics. Normally, it leads to the development of anomalous meridional circulation and heat exchange, which may result in heat waves in summer and cold periods with heavy frosts in winter (Yeh 1949; Rex 1950; Charney and DeVore 1979; Lupo et al. 1997, 2012; Sillmann et al. 2011; Masato et al. 2013; Mokhov et al. 2013). Extreme weather and climate events usually occur under conditions of long-term blocking of zonal circulation. In winter, blocking affects cold advection, reinforces the Siberian High, and leads to severe cold air outbreaks in East Asia (Joung and Hitchman 1982; Takaya and Nakamura 2005a). In summer, blocking often brings warmer and drier conditions to the areas it impacts, resulting in high temperatures and drought (Lupo et al. 2012); meanwhile, cold air brought by persistent blocking and cut-off lows meets warm, moist air from west of the western Pacific subtropical high, which provides a favorable background for long-lasting precipitation in East Asia. An important twin blocking pattern over the Urals and in northeastern Asia results in Meiyu (Li et al. 2001).

Because blocking plays a key role in extreme weather, it is vital to ensure that models can simulate it reliably (D’Andrea et al. 1998; Scaife et al. 2010; Barnes and Hartmann 2010; Vial and Osborn 2012; Barnes et al. 2012). Phase 5 of the Coupled Model Intercomparison Project (CMIP5) provides an opportunity to better evaluate blocking highs compared with CMIP3 because of improvements in model simulation skill (Taylor et al. 2012). Masato et al. (2013) used CMIP5 models to investigate the frequencies of blocking highs in both summer and winter and found that present-day blocking frequencies are generally underestimated and that blocking frequency will decrease in the 21st-century Northern Hemisphere (NH) under Representative Concentration Pathway (RCP) 8.5. Similar conclusions can also be found in other studies (e.g., Dunn-Sigouin and Son 2013a; Christensen et al. 2013; Cheung and Zhou 2015). However, the trend of sector blocking might not agree with and might even be opposite to the overall trend of NH blocking (e.g., Masato et al. 2013; Mokhov et al. 2014). Although summer blocking is predicted to decrease in the NH in general, high-latitude blocking may actually increase, indicating that it is still uncertain whether blocking frequency over all regions will decrease in the future. Mokhov et al. (2014) also pointed out that while the blocking frequency is decreasing for the NH as a whole, there is an opposite change, a general increase in blocking frequency, for the Euro-Atlantic region in winter and summer and for the entire year during the 21st century for both RCP scenarios analyzed.

The important impact of blocking on climate for the whole NH and for individual regions (Masato et al. 2013) has led researchers to focus on evaluating the ability of the CMIP5 models to simulate and project blocking over the whole NH or the Euro-Atlantic region and Pacific (e.g., Dunn-Sigouin and Son 2013a; Masato et al. 2013; Mokhov et al. 2013, 2014). However, 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). In particular, there have been very few studies analyzing model simulations in key regions of Eurasia for the East Asian climate.

Previous research has documented the relationship between blocking highs and East Asian weather and climate, especially for blocking over the Urals (e.g., Cheung and Zhou 2015), Baikal (e.g., Liu et al. 2012), and Okhotsk (e.g., Nakamura and Fukamachi 2004; Takaya and Nakamura 2005a) regions. These are considered to be the key regions for weather and climate effects related to blocking in East Asia (Ding and Krishnamurti 1987; Takaya and Nakamura 2005b). Although Urals blocking has been studied in terms of its impact on the East Asian winter climate in the projec-
tions of 20 CMIP5 models (Cheung and Zhou 2015), previous studies have lacked sufficient evaluation of the performance of CMIP5 models in simulating blocking and details of the implications of blocking in the future, in the Urals, Baikal, and Okhotsk regions. In this paper, we attempt to address the following questions: (1) How do the CMIP5 models perform in simulating blocking in Eurasia? (2) How will blocking change in the Urals, Baikal, and Okhotsk regions? The results show that the simulations and projections of CMIP5 models for blocking in Eurasia are different from those in the NH as a whole. These results may be vital in improving the forecasting of extreme weather and climate events in East Asia under a warming climate.

This paper is organized as follows. Section 2 describes the data and methods. Section 3 presents the simulation of blocking in the Urals, Baikal, and Okhotsk regions, including instantaneous blocking and blocking episodes of different duration. Section 4 uses the projection of 5 CMIP5 models to analyze future changes in blocking, including instantaneous blocking and blocking episodes. The results are summarized and discussed in Section 5.

2. Data and methodology

2.1 Data

Considering the model data, dynamical frame, resolution, and so on, we selected 13 CMIP5 models (Table 1) for analysis of their ability to simulate recently observed blocking. For better identification of models in this paper, model names are followed by their number in Table 1 (e.g., BCC-CSM1.1 (1) means BCC-CSM1.1 is number 1 in Table 1). We use historical simulations of 50 years for the period 1956–2005; historical runs with full climatic forcing are referred to as the “20th-century experiment.”

To match the 1956–2005 timescale of the “20th-century experiment,” we use a projection of 50 years for future changes. The model data used in this paper are the RCP4.5 and RCP8.5 runs from the five climate models (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) that have produced better simulations than the other eight models for the 20th century. RCP4.5 runs presume that additional radiative forcing will reach approximately 4.5 W m\(^{-2}\) at the top of the atmosphere; similarly, RCP8.5 runs simulate rising radiative forcing of 8.5 W m\(^{-2}\).

In this paper, we compare the blocking climatology obtained from historical geopotential height data with that of the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis (NNR) data during the same period as the historical simulations. In addition, the Niño3 sea surface temperature (SST) (5°S–5°N, 150–90°W) of the equatorial Pacific from NCEP/NCAR is used to confirm El Niño (La Niña) years. An El Niño (La Niña) year is one in which the annual Niño3 SST index exceeds +1 (−1) standard deviation. Accordingly, El Niño years are determined to be 1957, 1965, 1969, 1972, 1982, 1983, 1987, 1997, and 1998 and La Niña years are determined to be 1956, 1964, 1967, 1971, 1974, 1975, 1985, 1988, and 1999.

In addition, wintertime represents the cold season (November, December, January, February, March, and April), and summertime denotes the warm season (May, June, July, August, September, and October).

2.2 Blocking Index

Certain blocking has a significant influence on the weather and climate of East Asia: we focus mainly on the Urals (50–60°N, 40–70°E), Baikal (50–60°N, 80–110°E), and Okhotsk (50–60°N, 120–150°E) regions (Li et al. 2007). This criterion of three key regions was initiated by the China Meteorological Administration and is accepted by most meteorologists in China to define blocking episodes in East Asia.

In this study, we employ the blocking index defined by Tibaldi and Molteni (1990). Here the criteria for instantaneous blocking and a blocking episode (timescale of 4 days) also follow Tibaldi and Molteni (1990). A sector blocking episode is defined as instantaneous blocking that occurs over at least 15° of longitude for at least four consecutive days.

<table>
<thead>
<tr>
<th>Number</th>
<th>Model name</th>
<th>Country</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BCC-CSM1.1</td>
<td>China</td>
<td>64×128 T42</td>
</tr>
<tr>
<td>2</td>
<td>CanESM2</td>
<td>Canada</td>
<td>64×128 T42</td>
</tr>
<tr>
<td>3</td>
<td>CCSM4</td>
<td>America</td>
<td>192×288</td>
</tr>
<tr>
<td>4</td>
<td>CMCC-CESM</td>
<td>Italia</td>
<td>48×96</td>
</tr>
<tr>
<td>5</td>
<td>CNRM-CM5</td>
<td>France</td>
<td>128×256 TL127</td>
</tr>
<tr>
<td>6</td>
<td>FGOALS-g2</td>
<td>China</td>
<td>60×128</td>
</tr>
<tr>
<td>7</td>
<td>GFDL-CM3</td>
<td>America</td>
<td>90×144</td>
</tr>
<tr>
<td>8</td>
<td>GFDL-ESM2G</td>
<td>America</td>
<td>90×144</td>
</tr>
<tr>
<td>9</td>
<td>IPSL-CM5A-LR</td>
<td>France</td>
<td>96×96</td>
</tr>
<tr>
<td>10</td>
<td>MIROC-ESM</td>
<td>Japan</td>
<td>64×128 T42</td>
</tr>
<tr>
<td>11</td>
<td>MPI-ESM-MR</td>
<td>Germany</td>
<td>96×192</td>
</tr>
<tr>
<td>12</td>
<td>MRI-CGCM3</td>
<td>Japan</td>
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3. Simulation of Blocking Frequency in the Historical Run

3.1 Simulation of Instantaneous Blocking Frequency in Eurasia

We first confined our analysis to instantaneous blocking frequency using the 13 climate models and a multimodel ensemble mean for the three key regions. Blocking frequency by NNR during 1956–2005 is higher in the Urals and Okhotsk regions than in the Baikal region (Fig. 1), which also presents seasonal variation. Although there is comparably less blocking in the Baikal region, the blocking here has an important impact on weather and climate in East Asia (e.g., Zhang and Tao 1998). The least blocking occurs in the three key regions during September–November, and more blocking occurs during other months. Especially during June–August, the important twin blocking pattern (Li et al. 2001) over the Urals and Okhotsk regions is illustrated.

Figure 2 indicates the difference in monthly blocking frequency between the 13 models and the NNR and between the CMIP5 ensemble value and the NNR over Eurasia (40°–160°E) from 1956 to 2005. As shown in Fig. 2, the instantaneous blocking frequency simulated by most of the 13 climate models is generally underestimated compared with the reanalysis data, and the positive bias is less robust than the negative bias. To be specific, most of the negative bias is significant at the 0.05 level. However, except for the Okhotsk region, the positive bias is not significant for other regions. The difference in blocking frequency calculated by the CMCC-CESM (4), FGOALS-g2 (6), GFDL-CM3 (7), GFDL-ESM2G (8), IPSL-CM5A-LR (9), MIROC-ESM (10), MPI-ESM-MR (11), MRI-CGCM3 (12), and NorESM1-M (13) models and the NNR data is positive in Okhotsk region from January to May, which indicates that this blocking frequency is overestimated by these nine models (especially FGOALS-g2 (6), GFDL-CM3 (7), IPSL-CM5A-LR (9), MIROC-ESM (10), and MRI-CGCM3 (12)). In addition, the BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), and CNRM-CM5 (5) simulations differ from those of the other models: the simulated blocking frequency is underestimated in Okhotsk region from January to April. Although the multimodel mean reveals significant overestimation during January–April over the Okhotsk region, it is significantly smaller than that from the NNR data for most months in the Urals region and for summertime in the whole Eurasia. In addition, almost all of the models underestimate instantaneous blocking frequency significantly in June–August. A comparison of Fig. 1 with Fig. 2 shows that instantaneous blocking frequency is underestimated by most of the CMIP5 models (especially the model ensemble mean) when and where real blocking frequency is relatively high in Eurasia, whereas Okhotsk blocking during wintertime shows the opposite characteristics: even the frequency of blocking is relatively high.

Taylor diagrams provide a visual framework for comparing model results to a reference model or, most commonly, to observations (Taylor 2001). It is therefore common to use a Taylor diagram in the evaluation of CMIP models. Here, Taylor diagrams are used to quantify the correspondence between modeled and observed (NNR) instantaneous blocking frequencies based on longitude spans from 40°E to 150°E in Eurasia (Fig. 3), providing a quantitative description of the simulation ability of the 13 CMIP5 models given above.

As shown in Fig. 3a, with the exception of the FGOALS-g2 (6), IPSL-CM5A-LR (9), and MIROC-ESM (10) models, the correlation coefficients between the instantaneous blocking frequency from NNR data and that modeled by the other 10 CMIP5 models and the ensemble mean all generally exceed 0.9 throughout the year for Eurasia, especially the correlation coefficients for the CNRM-CM5 (5) and GFDL-ESM2G (8) models, which reach 0.99. The standard deviations
and root-mean-square errors of the BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), GFDL-ESM2G (8), MPI-ESM-MR (11), and MRI-CGCM3 (12) models and the model ensemble mean are close to those of the NNR data (difference does not exceed 0.5), while those of the other six models are larger than those of the observed data.

The situations in summertime and wintertime are shown in Figs. 3b and 3c, respectively. In summertime, correlation coefficients between instantaneous blocking frequency modeled by seven of the CMIP5 models and that from the NNR data are all less than 0.9, the standard deviations of eight of the model simulations are close to that of the NNR data, and the root-mean-square errors of the GFDL-ESM2G (8) and MPI-ESM-MR (11) model simulations are relatively small. In wintertime, apart from the MIROC-ESM (10) model, correlation coefficients between instantaneous blocking frequencies modeled by the other models or the ensemble mean and NNR data all exceed 0.8.
The standard deviations of the BCC-CSM1.1 (1), CanESM2 (2), and CCSM4 (3) models are less than that of the NNR data, while the standard deviations of the other models (especially FGOALS-g2 (6), GFDL-CM3 (7), IPSL-CM5A-LR (9), and MIROC-ESM (10)) are larger and the root-mean-square errors of BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), GFDL-ESM2G (8), and MRI-CGCM3 (12) are relatively small. Accordingly, these five models (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) may have a better ability to simulate instantaneous blocking frequency in Eurasia. Certainly, further verification is needed to evaluate the simulation ability of these five models for blocking episodes.

The Taylor diagrams reveal that most of the CMIP5 models simulate instantaneous blocking frequency better in wintertime than in summertime. As the 13-model ensemble mean includes information from some models (e.g., FGOALS-g2 (6), IPSL-CM5A-LR (9), and MIROC-ESM (10)) with unsatisfactory simulation performance, the ensemble mean does not give the best result and is not as good as BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8). This indicates that the simulation performance of the ensemble mean is improved not by an increase in the number of ensemble models but by the simulation quality of the models selected.

3.2 Simulation of Frequency of Blocking Episodes with Different Duration in the Three Key Regions

The frequency of blocking episodes of different duration is studied using simulation data from 13 models and observed (NNR) data in the Urals, Baikal, and Okhotsk regions.

As shown in Fig. 4, most of the 13 CMIP5 models and the ensemble mean reproduce the exponential distribution of blocking episode frequency with increasing duration in the Urals region. The diminishing trend of blocking episode frequency as the duration
increases from 4 days to more than 9 days is also reproduced. However, the frequency of blocking episodes is underestimated in the Urals region, especially in summertime. For a blocking duration of 4 days, only BCC-CSM1.1 (1), CanESM2 (2), and CCSM4 (3) give frequencies close to the observed value (2.7 days yr⁻¹); the frequency is less than that observed for the other models and the model ensemble mean. For a duration of 5–8 days, blocking episode frequency is considerably underestimated by CMCC-CESM (4), FGOALS-g2 (6), IPSL-CM5A-LR (9), and MIROC-ESM (10). Most of the 13 CMIP5 models can better
simulate the higher frequency of long-duration (more than 9 days) blocking episodes in wintertime than in summertime. However, only the value of long-duration blocking episode frequency simulated by BCC-CSM 1.1 (1) is close to the observed value (0.6 days yr\(^{-1}\)), while the other models underestimate this frequency.

In the Baikal region (Fig. 5), the frequency of blocking episodes with a duration of 4 days is 1.3 days yr\(^{-1}\) in NNR data, which is underestimated by 12 of the 13 CMIP5 models and overestimated only a little (1.6 days yr\(^{-1}\)) by BCC-CSM1.1 (1). The higher frequency of short-duration (4 days) blocking episodes in summertime than in wintertime is reproduced by BCC-CSM1.1 (1), CNRM-CM5 (5), IPSL-CM5A-LR (9), and MRI-CGCM3 (12). For blocking durations of 5–8 days, the model ensemble mean of blocking
episode frequency is approximately consistent with that from NNR. The frequency of blocking highs of long duration (more than 9 days) is 0.15 days yr$^{-1}$ and is slightly higher in summertime than in wintertime. This annual value is reproduced by BCC-CSM1.1 (1), CCSM4 (3), IPSL-CM5A-LR (9), MIROC-ESM (10), MRI-CGCM3 (12), and NorESM1-M (13). However, the frequency of long-duration (more than 9 days) blocking episodes is underestimated by most of these CMIP5 models in the Baikal region.

In the Okhotsk region (Fig. 6), the frequency of blocking episodes with short duration (4 or 5 days) simulated by most of the 13 models is comparable to the observed value of 1.5 days yr$^{-1}$ or 1.3 days yr$^{-1}$, while the frequency of 5-day blocking episodes modeled by IPSL-CM5A-LR (9), MIROC-ESM (10), and
NorESM1-M (13) is unrealistically larger than the frequency of 4-day blocking episodes. Models also reproduce the higher frequency of blocking episodes with short duration (4–5 days) in wintertime than in summertime. For blocking episodes with medium duration (6–8 days), the modeled frequency is generally higher in wintertime and less in summertime than that observed. As in the Urals and Baikal regions, in the Okhotsk region, blocking episodes with long duration (more than 9 days) are infrequent (0.7 days yr\(^{-1}\); most occur in wintertime). The frequency of blocking episodes with long duration is overestimated by FGOALS-g2 (6), GFDL-CM3 (7), IPSL-CM5A-LR (9), MIROC-ESM (10), MPI-ESM-MR (11), and NorESM1-M (13), particularly IPSL-CM5A-LR (9), which gives a frequency of up to 2.5 days yr\(^{-1}\). The overestimation of blocking by IPSL-CM5A-LR (9) was also found by Mokhov et al. (2014), but with a focus on the Euro-Atlantic region. The frequency of blocking episodes with long duration simulated by BCC-CSM1.1 (1) and CNRM-CM5 (5) is consistent with the observed value. Because of the large bias of some models, the ensemble-mean frequency of blocking episodes with a long duration is 0.6 days yr\(^{-1}\) more than the observed value.

Blocking episode frequency is underestimated by most of the 13 CMIP5 models in the Urals and Baikal regions, especially for short-duration blocking episodes (4–5 days). This result is consistent with that of Dunn-Sigouin and Son (2013a), who claimed that CMIP5 models can reproduce NH blocking climatology reasonably well, although the frequency of Euro-Atlantic blocking, particularly blocking of relatively short duration, is significantly underestimated during the cold season. Otherwise, simulations in the Urals and Baikal regions in wintertime are superior to those in summertime. Modeled blocking episode frequency is near the observed value in summertime but is overestimated in wintertime in the Okhotsk region.

The 13 CMIP5 models reproduce the general characteristics of the frequencies of instantaneous blocking and blocking episodes. However, individual models are inconsistent with reanalysis results for some periods, such as blocking episode frequency simulated in summertime over the Urals and Baikal regions and in wintertime in the Okhotsk region. Blocking errors are attributable largely to atmospheric resolution (e.g., Matsueda et al. 2009; Ren et al. 2009). Three models (CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) of the five (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) that simulate blocking better tend to have higher resolution in Table 1. However, the resolution of BCC-CSM1.1 (1) and CanESM2 (2) is not as high as that of CCSM4 (3), CNRM-CM5 (5), GFDL-CM3 (7), GFDL-ESM2G (8), MPI-ESM-MR (11), MRI-CGCM3 (12), and NorESM1-M (13). This indicates that resolution is one possible cause for the performance of the models. However, there are other factors affecting model blocking simulation, including misrepresentation of surface boundary conditions and uncertainties in physical parameterizations that lead to biases in the time-mean flow and high-frequency eddies (e.g., Matsueda et al. 2009; Scaife et al. 2010, 2011).

Because they have the same characteristics as errors in Europe-northeastern Atlantic (EA) blocking simulations, the blocking errors in the Urals and Baikal regions can be explained primarily by the problems mentioned above that lead to underestimation of blocking frequency by CMIP5 models. However, for blocking in the Okhotsk region (which is part of the North Pacific (PA) blocking), limited model resolution and energy transfer from the time-mean flow are not likely to be direct causes of the blocking frequency overestimation in the models (Dunn-Sigouin and Son 2013a). Dunn-Sigouin and Son (2013b) ascribed differences in model blocking biases in the EA and PA, especially the opposite sign of EA blocking and PA blocking during most seasons, to stronger interaction between quasi-stationary waves and transient waves over the North Pacific but a weaker interaction over the North Atlantic.

Studies have shown that SST errors generate much of the blocking bias (Scaife et al. 2010, 2011). The simulation bias of the El Niño-Southern Oscillation (ENSO: a leading mode of interannual-to-interdecadal variation of global tropical SST), which may dominate long-term changes in the coupled climate system, may be an explanation for blocking simulation bias (Vecchi et al. 2006). Previous studies have indeed revealed that blocking variation throughout the world is governed by ocean-atmosphere variability associated with ENSO (Renwick and Wallace 1996; Chen and Dool 1997; Wiedenmann et al. 2002). And it is reported that ENSO has significant impacts on the blocking in these three key regions: blocking is suppressed (enhanced) during the winter of El Niño (La Niña) years (Li et al. 2010). Generally, abnormal distribution of SSTs influences blocking by motivating teleconnection in the middle to high latitudes (Wu and Wang 1998), such as in El Niño winter; teleconnection in the central Pacific Northern Pacific-North America pattern can be easily identified (Yang and Luo 2014).
A negative anomaly at 500 hPa geopotential height in the Northern Pacific extends to the west and up to the Urals region, resulting in less blocking in Eurasia (Li et al. 2010). These conclusions led us to investigate the influence of ENSO as simulated in the CMIP5 models on the model bias of blocking in Eurasia. As blocking in the Baikal region is less than in the other regions and thus shows comparably small variation during different ENSO phases, here we illustrate simulations of blocking events in El Niño / La Niña years by CMIP5 models and NNR for all months in the Urals and Okhotsk regions during 1956–2005, as shown in Figs. 7 and 8. It is shown that simulations of blocking events in El Niño / La Niña years by the five

![Graphs showing blocking events simulation](image-url)
models (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) are close to the NNR data, especially the magnitude of blocking event frequency. This indicates that model simulations of blocking depend on the simulation of ENSO to some extent.

Figures 7 and 8 also show that only BCC-CSM1.1 (1) and GFDL-ESM2G (8) can reproduce the greater
frequency of blocking events in La Niña years than in El Niño years, indicating that most of the CMIP5 models may not have the ability to simulate ENSO well. In fact, the ability of the CMIP5 models to simulate ENSO is very important and is the foundation for further simulations related to ENSO. Although CMIP5 models are superior to CMIP3 models, climate models still require improvement to properly simulate and project ENSO (Yeh et al. 2012; Bellenger et al. 2013). As stated by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, AR4), there is serious, systematic bias between modeled ENSO and ENSO in the real world, for both the climate mean state and the variability (Van Oldenborgh et al. 2005; Stevenson 2012; Yeh et al. 2012). Zhang et al. (2014) compared 17 CMIP5 models and pointed out that the ENSO simulation of BCC-CSM1.1 (1) is reasonable at “medium-better level.” A study by Gong et al. (2014) shows that the correlation coefficient between the East Asian winter monsoon index and the Niño-3.4 index exceeds the 95 % and 99 % confidence level, respectively, in three (BCC-CSM1.1 (1), CanESM2 (2), and CNRM-CM5 (5)) out of the five models, which may explain the good performance of BCC-CSM1.1 (1), CanESM2 (2), and CNRM-CM5 (5) in our study. Simulations of the CMIP5 models in field of 500 hPa geopotential height between El Niño and La Niña years show that not all of the models with better simulation ability in blocking frequency in El Niño and La Niña years can reproduce ENSO-related large-scale circulation (Figs. not shown). This indicates that ENSO is just one factor related to simulation bias in blocking frequency and cannot explain the whole bias, suggesting that the simulation bias of CMIP models is a complex issue. The exact causes for the simulation bias of CMIP5 models in blocking frequency need further study.

4. Blocking frequency projections from the early to middle 21st century

We analyzed the performance of the CMIP5 models in the three key regions, and the simulations show some biases compared with the NNR. However, they broadly reproduce the blocking climatology and its long-term variation. Five models (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) perform better in simulating blocking in Eurasia. We now consider the projected changes in blocking frequency during the period 2016–2065. Hereafter, in this section, we describe the blocking frequencies derived from the five-model ensemble mean as simply the ensemble mean under the RCP4.5 and RCP8.5 radiative concentration pathways.

4.1 Projections of instantaneous blocking frequency in Eurasia

Figure 9 presents the difference in instantaneous blocking frequency between ensemble-mean modeled values in the first half of the 21st century (2016–2065) and the historical run in the late 20th century (1956–2005) under the different scenarios. As shown in the left panels in Fig. 9, the instantaneous blocking frequency from January to May increases slightly under RCP4.5 (0.4–0.8 days yr$^{-1}$) in the first half of the 21st century compared with the historical run, especially in two sectors (60–70°E; 120–150°E). The instantaneous blocking frequency decreases by 0.4–1.2 days yr$^{-1}$ in summertime, especially in the Okhotsk region. From August to December, a comparatively small increasing trend is present in the same sectors as during January–March. Overall, the range of the blocking frequency increase is less than the range of the decrease irrespective of the radiative pathway, RCP4.5 or RCP8.5. In addition, the decreased scope of instantaneous blocking frequency is a little larger under the high radiative concentration pathway of RCP8.5 than under the intermediate radiative concentration pathway of RCP4.5. For annual instantaneous blocking frequency and its 80 % spread (Fig. 10), blocking frequency under RCP4.5 and RCP8.5 is close to that of the historical run. Only east of the Urals region and in the Okhotsk region does instantaneous blocking frequency increase under a warmer climate. In addition, it is shown that the five models selected for the projection are consistent with each other, thereby supporting their use for this purpose.

Previous studies (Matsueda et al. 2009; Dunn-Sigouin and Son 2013a, b; Masato et al. 2013) analyzed changes in blocking frequency and found that the mean blocking frequency in the NH will decrease systematically in the 21st century, and such a decrease is more pronounced in the RCP8.5 run. Considering the differences in the definition of the blocking index, the timescale of the data, and the survey regions, this more notable decrease in mean blocking frequency in the RCP8.5 run can be regarded as a consistent conclusion of previous studies and our investigation. However, Cheung and Zhou (2015) suggested that the winter blocking index in the Urals region tends to increase in the RCP8.5 run. This signal can also be found in our study, which reconfirms that blocking variance is different in the three key regions.
4.2 Projections of the frequency of blocking episodes of different duration in the three key regions

In this section, projections of the frequency of blocking episodes of different duration are studied to determine the characteristics of blocking episode variability in the three key regions under RCP4.5 and RCP8.5 in the first half of the 21st century. The frequency of blocking episodes of different duration for the CMIP5 model ensemble mean during 2016–2065 under the RCP4.5 and RCP8.5 pathways and for the historical run and NNR data during 1956–2005 for the three key regions is illustrated in Fig. 9. Differences in instantaneous blocking frequencies between the CMIP5 model ensemble mean and historical run for each month over Eurasia during 2016–2065 under the RCP4.5 and RCP8.5 pathways (unit: day). Dots indicate statistical significance at the 0.05 level. The white dashed lines indicate domains of the three regions.

Fig. 10. Longitudinal distribution of annual instantaneous blocking frequencies for the historical run, RCP4.5, and RCP8.5 runs (lines) and 80% spread (shading) of the five models. The red line and shading are for RCP4.5. The blue line and shading are for RCP8.5. The black line and gray shading are for the historical run. The black dashed lines indicate domains of the three regions.
As there is better blocking simulation by the five models in the “20th-century experiment,” the character of their historical run is very close to that of NNR. Accordingly, the discussion here focuses mainly on the projection and NNR. As shown in Fig. 11a–d, the model ensemble means of RCP4.5 and RCP8.5 predict a value of 1.2 days yr\(^{-1}\) for the frequency of blocking episodes with short duration (4 days) in the Urals region. Compared with the present observed value of 2.7 days yr\(^{-1}\), blocking episodes with short duration decrease by \(\sim 60\%\) in both wintertime and summertime in the first half of the 21st century.

The frequency of 5-day blocking episodes decreases by \(\sim 40\%\) under RCP4.5 and RCP8.5. For blocking episodes with a duration of 6–9 days, the model ensemble-mean frequency is almost the same under RCP4.5 as under RCP8.5, showing a downward trend in both cases. The model ensemble means of RCP4.5 and RCP8.5 predict values of 0.37 days yr\(^{-1}\) and 0.34 days yr\(^{-1}\), respectively, for the frequency of long-duration blocking episodes (more than 9 days), decreasing by \(\sim 40\%\) compared with the observed value of 0.6 days yr\(^{-1}\). On the whole, blocking episodes in the Urals region decrease under RCP4.5 or RCP8.5 in
the first half of the 21st century, especially blocking episodes with short duration. The magnitude of the decrease is comparable under the two RCP scenarios. In addition, blocking episode frequency is higher in wintertime than in summertime in the first half of the 21st century.

For the key region of Baikal (Figs. 11e–h), the frequency of blocking episodes with short duration (4 days) modeled by the ensemble means of RCP4.5 and RCP8.5 decreases by ~45% and 50%, respectively, in the first half of the 21st century. The model ensemble mean has slightly more 4-day blocking episodes in wintertime than in summertime, in contrast to the observations and historical run. The frequency of 5–9-day blocking episodes from the ensemble means is a little less than the observed value, which is still less than but close to that of the historical run. The model ensemble means for RCP4.5 and RCP8.5 both predict a downward trend in the frequency of long-duration (more than 9 days) blocking episodes compared with the observed value of 0.15 days yr\(^{-1}\), which is greater in summertime than long-duration blocking in wintertime.

For the key region of Okhotsk (Figs. 11i–l), the frequency of short-duration (4 days) blocking episodes from the ensemble means of RCP4.5 and RCP8.5 decreases by ~10% and 5%, respectively, in the first half of the 21st century compared with the observed value of 1.5 days yr\(^{-1}\). The frequencies of 5–9-day blocking episodes in the ensemble means of RCP4.5 and RCP8.5 are almost the same as the observed value and historical run. The frequency of long-duration (more than 9 days) blocking episodes increases and is almost the same under RCP4.5 and RCP8.5. Blocking episodes with long duration modeled by the ensemble means of RCP4.5 and RCP8.5 occur more often in wintertime than in summertime. Under RCP4.5, the frequency of blocking episodes with long duration increases slightly compared with the observed value.

Dunn-Sigouin and Son (2013a) pointed out that the exact reasons for the decrease in PA and EA blocking frequencies in RCP8.5 integrations are not clear. According to their study, changes in the mean flow likely contribute to the decreasing trend in the Urals and the increasing trend in the Okhotsk region in the first half of the 21st century generated in our study, as there is weakened low-frequency variability over the North Atlantic and strengthened low-frequency variability over the eastern North Pacific. Meanwhile, future changes in upper tropospheric zonal wind may also be a factor in future changes in blocking. Mizuta (2012) pointed out that, under RCP4.5, there is an enhanced polar jet in the North Pacific, leading to an enhanced mean growth rate of surface cyclones. However, in the Atlantic, no such signal is found. In addition, future changes in ENSO may also contribute. In RCP8.5 integrations, there will be more frequent El Niño events (or less frequent La Niña events) and the Niño-3.4 index shows a weak hint of enhanced El Niño events (Dunn-Sigouin and Son 2013a), resulting in fewer blocking events in the future.

Barnes et al. (2012) implied that decreased blocking frequency means a reduction in weather extremes in the 21st century, but this may be overconfident. For example, Wang et al. (2010) found that although winter blocking has decreased in the Urals region in the past few decades, its relationship with the East Asian winter (Cheung and Zhou 2015). As we discussed in the Introduction, blocking in the key regions of the Urals, Baikal, and Okhotsk has an important influence on East Asian climate and future variance also shows uncertainty in different studies. This uncertainty might present a challenge for accurate prediction of subseasonal and long-term variation of the East Asian winter climate (Cheung and Zhou 2015).

5. Conclusions and discussion

This study investigates the CMIP5 model climatology of atmospheric blocking over the Urals, Baikal, and Okhotsk regions, which significantly influences weather and climate in East Asia. Historical simulations are analyzed to evaluate the performance of 13 CMIP5 models, and possible changes in the first half of the 21st century are then predicted using the RCP4.5 and RCP8.5 pathways.

Comparison with NNR data (Fig. 2) reveals that instantaneous blocking frequencies over these three key regions are on average underestimated in summertime, although modest differences appear among the individual models. However, instantaneous blocking frequencies in wintertime modeled by most CMIP5 models are underestimated in the Urals and Baikal regions but are overestimated in the Okhotsk region. Furthermore, the multimodel ensemble mean generally underestimates blocking frequency in the
whole year, overestimating blocking frequency in the Okhotsk region only in wintertime. A quantitative analysis of instantaneous blocking frequencies (Fig. 3) reveals that the correlation coefficients between the modeled and reanalysis blocking frequencies are higher in wintertime than in summertime. Overall, the CMIP5 models broadly reproduce the characteristics of instantaneous blocking frequency in Eurasia. The simulations of instantaneous blocking frequency by BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRMCM5 (5), and GFDL-ESM2G (8) are superior to those of the other eight models.

Most of the 13 CMIP5 models reproduce the exponential distribution of blocking episode frequency with increasing duration in the Urals, Baikal, and Okhotsk regions (Figs. 4–6). Blocking episode frequency is underestimated by most of the 13 CMIP5 models in the Urals and Baikal regions, especially for short-duration blocking episodes (4–5 days). The simulations are superior in wintertime in the Urals and Baikal regions. Modeled blocking episode frequency is close to the observed value in summertime but is overestimated in wintertime in Okhotsk region. The possible cause for the unsatisfying performance of the models is investigated, and it is shown that the five models (BCC-CSM1.1 (1), CanESM2 (2), CCSM4 (3), CNRM-CM5 (5), and GFDL-ESM2G (8)) that are better at simulating blocking may be superior because of their resolution and prior ability to simulate ENSO (Figs. 7–8). However, the crucial factors of simulation bias of CMIP5 models in blocking are unclear over the three key regions of Eurasia. ENSO is not the only factor and cannot explain the whole simulation bias, which demonstrates again that the difference in the simulation bias of CMIP models in blocking is very complicated. Due to the limitation of this work, this issue is not addressed at present. More model outputs are needed for deeper research on evaluating the simulation ability of climate models in blocking. Particularly, further study is required to explore the difference in blocking behaviors in the three key regions.

Model projections of instantaneous blocking frequency for the first half of the 21st century (2016–2065) are examined under the RCP4.5 and RCP8.5 pathways over the Urals, Baikal, and Okhotsk regions (Fig. 9). The RCP4.5 projection yields a significantly increasing frequency during January–May, a decreasing frequency during June–August, and a slightly increasing frequency during September–December. The RCP8.5 projection gives similar results to the RCP4.5 projection, showing that the increasing magnitude of instantaneous blocking frequency is a little less than the decreasing magnitude. The five-model ensemble-mean blocking episode frequency (Fig. 11) obviously decreases in the Urals and Baikal regions (especially blocking episodes with short duration) and increases a little in the Okhotsk region in the first half of the 21st century compared with the observed value. The model ensemble-mean frequency of blocking episodes with short duration decreases by ~60% and 50% in the Urals and Baikal regions, respectively, but is almost the same as the observed value in the Okhotsk region. The model ensemble-mean frequency of blocking episodes with long duration decreases by ~40% in the Urals but increases by no more than 5% in the Okhotsk region (under RCP4.5, 5%; under RCP8.5, 2%). The decreasing trend in the Urals and increasing trend in the Okhotsk region in the first half of the 21st century generated in our study can be explained from the aspect of changes in the mean flow, as there is weaker low-frequency variability over the North Atlantic and stronger low-frequency variability over the eastern North Pacific (Dunn-Sigouin and Son 2013a). Future changes in ENSO may also contribute. In RCP8.5 integrations, more frequent El Niño events (or less frequent La Niña events) may result in fewer blocking events (Dunn-Sigouin and Son 2013a).

We conducted a detailed investigation of the blocking climatology influencing weather and climate in East Asia and predicted possible changes in blocking frequency in a warmer climate, and these results are generally consistent with those of other studies of projected blocking over the NH. This study also shows that there is peculiarity of simulation and projection for regional blocking in Eurasia. Therefore, deeper study is needed for the next step of explaining why models show different simulation abilities and give different projections for blocking in these key regions.

In East Asian wintertime, previous studies proposed that the linkage between blocking in the Urals region and the wintertime monsoon is amplified in East Asia, especially after 1976/1977 (Wang 2008; Wang et al. 2010). In the 21st century, the influence of Urals blocking in East Asia may continue and even increase (Cheung and Zhou 2015). Baikal and Okhotsk blocking also play important roles in East Asian climate. Under a warmer climate, how will the relation between blocking in these key regions and other large-scale circulation features change? What will be the impact of blocking in East Asia in the future, especially on extreme weather and climate events like cold waves in winter and rainstorms in summer? These are all still open questions requiring further study.
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