Northern Hemisphere blocking climatology as simulated by the CMIP5 models

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Northern Hemisphere (NH) blocking climatology is examined using a subset of climate models participating in the Coupled Model Inter-Comparison Project phase 5 (CMIP5). Both historical and Representative Concentration Pathway (RCP) 8.5 integrations are analyzed to evaluate the performance of the CMIP5 models and to identify possible changes in NH blocking frequency and duration in a warmer climate. Comparison to reanalysis data reveals that CMIP5 models can reproduce the NH blocking climatology reasonably well although the frequency of Euro-Atlantic blockings, particularly those with relatively short duration, is underestimated in most models during the cold season. In several models, overestimation of the Pacific blocking frequency is also evident throughout the year. In comparison to historical integrations, RCP 8.5 integrations show statistically significant decrease in blocking frequency over both the north Pacific and north Atlantic regions, with a weak hint of increasing blocking frequency over western Russia. This change is clear from autumn to winter, and dominated by changes in relatively short-lived blocking events.
1. Introduction

Atmospheric blocking is one of the most dramatic examples of extratropical low-frequency variability. Traditionally it refers to a synoptic-scale high pressure system, often accompanied by low pressure system(s) at lower latitudes, that remains quasi-stationary for days to weeks, interrupting the zonal flow (e.g., Rex 1950). Since blocking highs are persistent and quasi-stationary by definition, they affect surface weather and climate in a major way. For instance, a blocking high often causes a significant increase in surface temperature beneath it and enhanced storm activity around it (e.g., Trigo et al. 2004). Striking examples are the 2003 European and 2010 Russian heat waves, that resulted from exceptionally long-lasting blocking events. Both of them lead to record breaking surface air temperatures and significant increases in mortality rates [Black et al., 2004; Dole et al., 2011].

The crucial role that blocking plays in surface weather (especially in extreme weather) has underlined the need for the reliable simulation of blocking events by climate models. It is however well documented that climate models often underestimate Northern Hemisphere (NH) blocking frequency, especially over the North Atlantic and Europe (e.g., D’Andrea et al. 1998; Doblas-Reyes et al. 2002; Scaife et al. 2010; Barriopedro et al. 2010). While detailed causality is still an active area of research, this underestimation has been attributed to the limited model resolution, misrepresentation of surface boundary conditions and uncertainties in physical parametrizations that lead to the biases in the time-mean flow and high-frequency eddies (e.g., Matsueda et al. 2009; Scaife et al. 2010, 2011).
Recent studies have shown that the frequency of NH blocking events may decrease in the future, in response to global warming. By analyzing CMIP3 models, Barnes and Hartmann [2010] and Barnes et al. [2011] documented a statistically significant decrease in blocking frequency over both north Pacific and north Atlantic in the 21st century. They however found no evidence in blocking duration change. While a similar frequency change is also found in model sensitivity tests [Matsueda et al., 2009; Sillmann and Croci-Maspoli, 2009], different studies show slightly different results in duration change. For example, Sillmann and Croci-Maspoli [2009] showed a possible increase in maximum blocking duration over the Euro-Atlantic region, whereas Matsueda et al. [2009] showed a possible reduction in long-lived blocking events.

It should be noted that, despite of the importance of blocking events, only few studies (as listed above) have documented possible changes in blocking activities in a warmer climate. As a matter of fact, future projection of NH blocking highs was not commented in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Solomon et al. 2007) which is largely based on the CMIP3 data. This lack of documentation partly results from availability of daily data. Although blocking is typically examined using 500-hPa geopotential height or upper-tropospheric dynamic fields such as potential temperature on the 2-PVU surface or upper-tropospheric PV anomalies, these data sets were not archived in the CMIP3 in daily or sub-daily resolution. Of the few studies based on CMIP3 models, Barnes et al. [2011] used zonal wind, assuming geostrophic balance, to characterize the NH blocking climatology in the CMIP3.
The primary goal of this study is to examine the NH blocking climatology in the present and future climate as simulated by the CMIP5 models. Extending and updating previous studies, we evaluate state-of-the-art climate models in the context of present-day blocking climatology and document the multi-model projection of blocking frequency and duration in the 21st century. This goal is achieved by applying a hybrid blocking index [Dunn-Sigouin et al., 2012], that is essentially a combination of the two widely-used blocking indices, to daily 500-hPa geopotential height fields in both historical and RCP integrations.

2. Data and Methodology

The model data used in this study are historical and RCP 8.5 runs from a subset of climate models participating in the CMIP5 [Taylor et al., 2012]. Briefly, historical runs are 20th-century climate integrations with all observed climate forcings. RCP 8.5 runs are scenario integrations with a rapid warming, specifically with an anthropogenic radiative forcing of 8.5 \( \text{W m}^{-2} \) at 2100. All available models that archived daily geopotential height fields are used: i.e., a total of 17 models for historical integrations and 13 models for RCP 8.5 integrations as of June 2012 (Table 1). If multiple realizations are available, only the first ensemble member is considered.

All model output is first interpolated onto the lowest model resolution, namely 2.8° latitude by 2.8° longitude (Table 1). Blocking statistics are then derived using this interpolated data. To minimize the effect of internal variability in climatology, analyses are performed for a sufficiently long time period. Specifically, 40 years, 1966-2005 for historical runs and 2060-2099 for RCP 8.5 runs, are considered. The performance of the CMIP5 models is first evaluated by comparing the blocking climatology derived from historical
integrations to that of the National Centers for Atmospheric Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis (NNR, Kalnay et al. 1996). Future changes in blocking activities are then quantified by comparing historical runs with RCP 8.5 runs.

The blocking index employed in this study is a hybrid index which combines the two widely-used blocking indices in a simple way [Dunn-Sigouin et al., 2012]. A contiguous area of blocking anomalies is first identified from the 500-hPa geopotential height field, as in the Dole-Gordon type blocking index [Dole and Gordon, 1983], and then a reversal of the meridional gradient of geopotential height, as in the Tibaldi-Molteni type blocking index [Tibaldi and Molteni, 1990], is evaluated on the equatorward side of the blocking anomaly maximum. The spatio-temporal evolution of the blocking anomalies is assured by tracking the amplitude (A), spatial extent (S), overlap between successive days (O) and duration (D). The amplitude threshold (A) is set to 1.5 standard deviation of geopotential height anomalies over 30°-90°N for a 3-month period centered at a given month. The remaining threshold values are set to (S)=2.5x10^6 km^2, (O)=50% and (D)=5 days, for both NNR and CMIP5 data. See Dunn-Sigouin et al. [2012] for the details.

All results are shown in the multi-model mean. But, to illustrate inter-model differences and statistical uncertainty, individual models are also presented in the auxiliary materials.

3. Blocking climatology

Figure 1a presents NH blocking climatology from 40-year long NNR data (see also Dunn-Sigouin et al. 2012). Blocking frequency is shown as the number of days per year a blocked area occupies each grid point. As widely documented in the literature, two active
regions of blocking occurrence emerge: north Pacific (hereafter PA blocking) and Europe-northeastern Atlantic (EA blocking). The latter generally exhibits higher frequency than the former although the opposite is true during the summer (Fig. 2a). EA blocking also shows a more zonally-elongated geographical distribution than PA blocking, with a long tail to western Russia. In certain seasons, blocking activities over western Russia are separated from those over North Atlantic and western Europe (e.g., November in Fig. 2a), and referred to as Ural blocking.

The blocking climatology, derived from 17 CMIP5 historical runs, is illustrated in Figs. 1b-c. It is evident that the CMIP5 models can reproduce the overall geographical distribution of the NH blocking activities reasonably well. Noticeable biases are however present in amplitude (Fig. 1c). Most of all, EA blocking frequency is underestimated by about 30%. This is common to all the models analyzed in this study (Fig. S1) and consistent with previous modelling studies (e.g., D'Andrea et al. 1998; Scaife et al. 2010). In contrast, PA blocking frequency is overestimated by the models over broad regions. While this bias is less robust than EA blocking bias (see shading in Fig. 1 in midlatitudes; see also Fig. S1), it is still significant particularly on the poleward side of the climatological blocking frequency maxima. A similar overestimation was also reported in a recent study by Dunn-Sigouin et al. [2012] as well as in a few climate models participating in the CMIP3 [Scaife et al., 2010].

The above model biases in blocking frequency might be partly caused by the model resolution. It is well known that high-frequency eddy forcing, which is one of the most important maintenance mechanisms of blocking highs (e.g., Shutts 1983; Nakamura et al. 1983).
1997), is very sensitive to the model resolution. Matsueda et al. [2009], for instance, presented more accurate EA blocking simulation in a higher-resolution model integration. However, a direct comparison between IPSL-CM5A-MR and IPSL-CM5A-LR, whose difference is only model resolution (Table 1), shows a negligible difference in EA blocking frequency (Figs. S1c-d). A moderate increase in horizontal resolution instead leads to a slight decrease in EA blocking frequency. This result supports the finding of Scaife et al. [2011] that EA blocking frequency is more sensitive to surface boundary conditions than atmospheric model resolution. Matsueda et al. [2009] further indicated that the PA blocking frequency could be overestimated in a high-resolution model integration. However, no systematic relationship between PA blocking bias and model resolution is observed throughout the models (Fig. S1). This is largely consistent with Dunn-Sigouin et al. [2012] who showed that PA blocking frequency could be overestimated even in a coarse resolution model integration where high-frequency eddy activities are underrepresented. They suggested that the biases in time-mean flow could result in model biases in blocking frequency.

The seasonal cycles of blocking frequency are illustrated in Fig. 2. It presents the evolution of monthly-mean NH blocking frequency as a function of longitude. The number of blocking events are simply counted along a given longitude band from 30° to 90°N for a given month. The longitudinal distribution of blocking frequency and its seasonality is reasonably well reproduced in the multi-model mean (Figs. 2a-b). Underestimation of EA blocking frequency is largely confined to the cold season, whereas overestimation of PA blocking frequency is found throughout most of the year. It is also found that, although
the models successfully reproduce the summertime peak in PA blocking, it is delayed by a month from August to September.

Figure 3 shows the number of blocking events as a function of duration. The EA and PA blocking events, defined over 0-90°N and 25°W-42°E and 0-90°N and 151°E-220°W, respectively, are separately illustrated along with a total number of blocking events over whole NH. In general, the number of blocking events exhibits an exponential decrease with duration (Figs. 3a-b). Comparison of CMIP5 to NNR data, however, reveals that, although not statistically significant, short-lived blocking events, duration shorter than 9 days, are generally underrepresented by the models while long-lived ones are somewhat overrepresented (see black bars in Fig. 3c). The bias in short-lived blocking events is mostly due to EA blocking events (see blue bars in Fig. 3c). In most durations, PA blocking events show overestimation.

To identify the possible sources of model biases in blocking frequency climatology, high frequency eddy fields are further examined in Fig. 4. High-frequency eddy activities are quantified by using the standard deviation of 500-hPa geopotential height anomalies with periods shorter than 7 days. While the high-frequency eddy activities are in qualitatively good agreement with the NNR (Figs. 4a-b), the strength of both north Atlantic and north Pacific storm tracks is underestimated in the CMIP5 models (Fig. 4c). This underestimation is consistent with EA blocking frequency biases (compare Figs. 1c and 4c). However, a similar consistency is not found with PA blocking frequency biases. This result suggests that the formation and maintenance mechanism(s) of blocking highs may be different over the two basins [Tibaldi et al., 1997; Matsueda et al., 2009; Dunn-Sigouin et al., 2012].
4. Future changes

With model biases described above in hand, this section examines potential changes in blocking frequency and duration in a warmer climate. The multi-model mean climatology, derived from 40 years (2060-2099) of RCP 8.5 runs, are presented in Fig. 1d and compared with its counterpart derived from 40 years of historical runs (1966-2005) in Fig. 1e. Only 13 models, that have both historical and RCP 8.5 runs, are used to make a direct comparison.

The geographical distribution of blocking frequency in the future climate is quite similar to the one in the present climate (Fig. 1d). However, blocking frequency in a warmer climate is slightly decreased over the northeastern Pacific and northwestern Atlantic (Fig. 1e). While the decrease is rather weak, it is robustly found in several models (Fig. S5). This result agrees with previous findings [Matsueda et al., 2009; Sillmann and Croci-Maspoli, 2009; Barnes et al., 2011], and is consistent with high-frequency eddy changes which are predicted to be weakened upstream of the north Atlantic and north Pacific blocking regions (Figs. 4d-e).

In contrast to blocking frequency changes over the north Pacific and north Atlantic, blocking frequency over eastern Europe-Russia is predicted to increase in the future. This increase of the so-called Ural blocking frequency is relatively weak and not quite robust across the models (Fig. 1e). However, a general tendency is observed in a number of models (Fig. S5). In some models (e.g., HadGEM2-CC), the Ural blocking frequency change is statistically significant and even larger than PA blocking frequency change. The
increased high-frequency eddy activities upstream of the Ural region in a warm climate (Fig. 4e) further supports the potential increase in Ural blocking frequency.

The seasonal cycle of the NH blocking activities in the RCP 8.5 runs is compared with their historical counterparts in Figs. 2d-e. Again, overall geographical distribution and seasonality are quite similar to those in the present climate. It is further found that the reduced blocking frequencies observed over the north Pacific and north Atlantic occur primarily during the fall and winter seasons, although they extend into spring over the north Pacific (see also Fig. S6). Figures 3d-e presents blocking frequency change as a function of duration. A decrease in number of blocking events is found in all durations, with a larger decrease in shorter-lived blocking events. Although statistically insignificant, this result may suggest that the mean duration of individual blocking events would slightly decrease in a warmer climate.

5. Conclusions

This study examines the NH blocking climatology as simulated by the CMIP5 models. Both historical and RCP 8.5 runs are examined to evaluate the performance of the CMIP5 models in comparison to NNR and to identify possible changes in blocking frequency and duration in a warmer climate.

Comparison to reanalysis data reveals that the CMIP5 models can reproduce the NH blocking climatology reasonably well. It is however found that the EA blocking frequency is generally underestimated in most models during the cold seasons. This is mostly due to the short-lived blocking events with duration shorter than 9 days. In contrast, the PA blocking frequency is largely overestimated throughout the year for almost all dura-
tions. Although this result contrasts to previous modelling studies which have typically
documented underestimation of the blocking frequency over both the north Pacific and
Atlantic in a moderate-resolution climate model integration (e.g., D’Andrea et al. 1998;
Doblas-Reyes et al. 2002; Matsueda et al. 2009; Barriopedro et al. 2010), a similar result
is documented for the latest operational model [Dunn-Sigouin et al., 2012], and for certain
models participating in the CMIP3 [Scaife et al., 2010].

In comparison to historical integrations, the RCP8.5 integrations show a weak hint of
reduced blocking frequency over the north Pacific and north Atlantic especially during the
fall and winter. This result largely confirms previous findings that are based on different
data and different blocking indices [Matsueda et al., 2009; Sillmann and Croci-Maspoli,
2009; Barnes and Hartmann, 2010; Barnes et al., 2011]. In contrast to north Pacific
and north Atlantic blocking events, blocking events over eastern Europe and Russia, the
so-called Ural blocking, are predicted to marginally increase in a warmer climate.

Here it should be noted that the results presented in this study are largely insensitive
to the horizontal interpolation: Quantitatively similar results are found with raw data
(not shown). Overall results, however, could be sensitive to the choice of blocking index.
Although the TM type index [D’Andrea et al., 1998] shows qualitatively similar result
(see Fig. S9), other indices could show different results. Further analyses are needed.

The causes of model biases and possible reasons of future blocking changes are not
explicitly addressed in this study. While detailed analyses are needed, preliminary results
indicate that underestimation of blocking frequency over the Euro-Atlantic and a future
decrease in blocking frequency over the north Atlantic and north Pacific are consistent
with changes in upstream high-frequency eddy activities. In most CMIP5 models, high-frequency eddy activities are underrepresented in the present climate integrations and are predicted to be weakened in the future over the two basins. A similar consistency between high-frequency eddy activities and north Pacific blocking frequency biases, however, is not observed.

Acknowledgments. We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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Figure 1. Climatology of NH annual-mean blocking frequency: (a) NNR, (b) historical multi-model mean, (c) historical multi-model mean - NNR, (d) RCP 8.5 multi-model mean and (e) RCP 8.5 - historical multi-model mean. Black and colored contour intervals in (a,b,d) and (c,e) are 4 days and 2 days, respectively. The grey contour in (c,e) denotes the zero line and shaded areas denote differences greater than one standard deviation of individual model differences.
Figure 2. Seasonal cycle of the NH blocking frequency as a function of longitude: (a) NNR, (b) historical multi-model mean, (c) historical multi-model mean - NNR, (d) RCP 8.5 multi-model mean and (e) RCP 8.5 - historical multi-model mean. Black and colored contour intervals in (a,b,d) and (c,e) are 1 day and 0.5 days per month, respectively. the grey contour in (c,e) denotes the zero line and shaded areas denote differences greater than one standard deviation of individual model differences.
Figure 3. Number of blocking events as a function of duration: (a) NNR, (b) historical multi-model mean, (c) historical multi-model mean - NNR, (d) RCP 8.5 multi-model mean and (e) RCP 8.5 - historical multi-model mean. Black, blue and red bars denote blocking events over the NH, the EA and PA sectors, respectively. Shaded bars in (c,e) denote differences greater than one standard deviation of individual model differences.
Figure 4. Climatology of annual-mean standard deviation of 500-hPa high-frequency eddies with periods shorter than 7 days: (a) NNR, (b) historical multi-model mean, (c) historical multi-model mean - NNR, (d) RCP 8.5 multi-model mean and (e) RCP 8.5 - historical multi-model mean. Black and colored contour intervals in (a,b,d) and (c,e) are 10 m and 2 m, respectively. The grey contour in (c,e) denotes the zero line and shaded areas denote differences greater than one standard deviation of individual model differences.
Table 1. Description of CMIP5 models used in this analysis. Resolutions refer to atmospheric
model resolution and horizontal resolution is approximate for spectral models.

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<th>Model</th>
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<th>Horizontal res. (lat. x lon.)</th>
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<th>RCP8.5 run</th>
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</table>
Northern Hemisphere blocking climatology as simulated by the CMIP5 models

(Auxiliary Material)

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Figure S1: Same as Fig. 1c except for individual models. Contour interval is 2 days per year and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student $t$-test. Zero lines are omitted.
Figure S2: Same as Fig. 2c except for individual models. Contour interval is 1 day per year and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student t-test. Zero lines are omitted.
Figure S3: Same as Fig. 3c except for individual models. Shaded bars denote statistically significant differences at the 95 percent confidence level using a two-tailed student t-test.
Figure S4: Same as Fig. 4c except for individual models. Contour interval is 2 \( m \) and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student \( t \)-test. Zero lines are omitted.
Figure S5: Same as Fig. 1e except for individual models. Contour interval is 2 days per year and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student $t$-test. Zero lines are omitted.
Figure S6: Same as Fig. 2e except for individual models. Contour interval is 1 day per year and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student t-test. Zero lines are omitted.
Figure S7: Same as Fig. 3e except for individual models. Shaded bars denote statistically significant differences at the 95 percent confidence level using a two-tailed student $t$-test.
Figure S8: Same as Fig. 4e except for individual models. Contour interval is 2 m and shaded areas denote statistically significant differences at the 95 percent confidence level using a two-tailed student $t$-test. Zero lines are omitted.
Figure S9: Same as Fig. 2 but for blocking frequencies derived using the TM type blocking index of D’Andrea et al. (1998).