Winter and Summer Northern Hemisphere Blocking in CMIP5 Models

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ABSTRACT
The frequencies of atmospheric blocking in both winter and summer and the changes in them from the twentieth to the twenty-first centuries as simulated in 12 models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) are analyzed. The representative concentration pathway 8.5 (RCP8.5) high emission scenario runs are used to represent the twenty-first century. The analysis is based on the wave-breaking methodology of Pelly and Hoskins. It differs from the Tibaldi and Molteni index in viewing equatorward cutoff lows and poleward blocking highs in equal manner as indicating a disruption to the westerlies. One-dimensional and two-dimensional diagnostics are applied to identify blocking of the midlatitude storm track and also at higher latitudes. Winter blocking frequency is found to be generally underestimated. The models give a decrease in the European blocking maximum in the twenty-first century, consistent with the results in other studies. There is a mean twenty-first-century winter poleward shift of high-latitude blocking but little agreement between the models on the details. In summer, Eurasian blocking is also underestimated in the models, whereas it is now too large over the high-latitude ocean basins. A decrease in European blocking frequency in the twenty-first-century model runs is again found. However, in summer there is a clear eastward shift of blocking over eastern Europe and western Russia, in a region close to the blocking that dominated the Russian summer of 2010. While summer blocking decreases in general, the poleward shift of the storm track into the region of frequent high-latitude blocking may mean that the incidence of storms being obstructed by blocks may actually increase.

1. Introduction
Atmospheric blocking is a crucial dynamical phenomenon in the extratropics and, as such, it has been studied since the advent of modern meteorology (Berggren et al. 1949; Rex 1950). Its impact on regional climate, particularly that of Europe, is evident (e.g., Trigo et al. 2004; Masato et al. 2012), generally leading to extreme cold conditions in winter and warmth during summer (Buehler et al. 2011). Weather forecasting models have shown an increasing ability to simulate blocking events. For example, Pelly and Hoskins (2003b) showed that the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system (EPS) was skillful for blocking onset and degraded on a one week time scale. Matsueda (2009) demonstrated reasonable skill in forecasting blocking in many of The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) extended-range numerical weather prediction models. Nevertheless, many climate models still have severe problems in simulating the observed occurrence of midlatitude blocking. D’Andrea et al. (1998) documented this bias in the original Atmospheric Model Intercomparison Project (AMIP) models and it remained a problem in the models participating in the phase 3 of the Coupled Model Intercomparison Project (CMIP3; e.g., Barnes et al. 2012; Scaife et al. 2010).

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The attribution of these errors is currently being investigated. Some have identified the relatively coarse horizontal resolution of climate models as the primary source of error (Matsueda 2009). Others have further looked at the behavior of models and attributed the poor performances to the bias in their mean state (Scaife et al. 2010). Barriopedro et al. (2010a,b) gave evidence that a bias in frequency was associated with excessive westerlies (which impede the reversal of the meridional gradient) and with a southward displacement of the jet stream. Limited resolution affects the transient eddy (gradient) and with a southward displacement of the jet stream. This response is closely related to the mean state changes (Woollings 2010; de Vries et al. 2013), which, in general, comprise strengthened westerly winds albeit with considerable uncertainty (e.g., Woollings and Blackburn 2012). Changes in summer blocking have received particularly little attention, yet the association of summer blocking with heatwaves means that summertime blocking will be of increasing concern from an impacts perspective (Barriopedro et al. 2011).

The aim of this paper is to take advantage of the new generation of climate models used within phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) to evaluate progress made in simulating blocking and the latest indications of how Northern Hemisphere blocking may change with enhanced greenhouse gases. A comprehensive picture of blocking in climate models is complicated by the use of several different (though related) blocking indices in the literature. Here, the basic methodology of Pelly and Hoskins (2003a, hereafter PH03) is followed as developed by Masato et al. (2012, 2013). One of the most fundamental differences between blocking indices is the dimensionality (i.e., whether blocking is identified as a function of longitude only or of both latitude and longitude). Both approaches have advantages and disadvantages. While one-dimensional (1D) indices identify only events that could be called classical midlatitude blocks, they can be very sensitive to the choice of latitude used. Meanwhile, 2D indices avoid this sensitivity yet can identify events far from the storm-track axis, which are of minor importance. Both 1D and 2D indices are used in this paper to develop a more complete picture of how the changes in blocking are related to changes in the jet streams and storm tracks. In particular, following Barnes et al. (2012) the 1D index is designed to follow the storm tracks as they shift between different model simulations, ensuring that any change in blocking is not a trivial consequence of a storm-track change. The data and methodology used will be presented in section 2. In the following two sections, the results for winter and summer, respectively, will be illustrated and discussed. Concluding remarks will be given in section 5.

2. Data and methodology

a. Data

The 12 coupled models considered are listed in Table 1 with acronym expansions listed. The two CMIP5 experiments considered here are the historical and representative concentration pathway 8.5 [RCP8.5; for a comprehensive list, see Taylor et al. (2012)]. The latter simulates a rising radiative forcing pathway leading to 8.5 W m$^{-2}$ at top of atmosphere (TOA) in 2100. The
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Model</th>
<th>Model expansion</th>
<th>Center</th>
<th>Horizontal resolution</th>
<th>Vertical levels (above 200 hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCC</td>
<td>BCC-CSM1.1</td>
<td>Beijing Climate Center, Climate System Model, version 1.1</td>
<td>Beijing Climate Center</td>
<td>T42</td>
<td>26(13)</td>
</tr>
<tr>
<td>CAN</td>
<td>CanESM2</td>
<td>Second Generation Canadian Earth System Model</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>T63</td>
<td>35(12)</td>
</tr>
<tr>
<td>CNRM</td>
<td>CNRM-CM5</td>
<td>Centre National de Recherches Méteorologiques Coupled Global Climate Model, version 5</td>
<td>Centre National de Recherches Meteorologiques (Toulouse, France)</td>
<td>T127</td>
<td>31(9)</td>
</tr>
<tr>
<td>EC-EARTH</td>
<td>EC-Earth</td>
<td>EC-Earth Consortium</td>
<td>EC-EARTH consortium (European Consortium)</td>
<td>T159</td>
<td>91(19)</td>
</tr>
<tr>
<td>IPSL</td>
<td>IPSL-CM5A-MR</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 5A, coupled with NEMO, mid resolution</td>
<td>Institut Pierre-Simon Laplace (France)</td>
<td>1.25° × 2.5°</td>
<td>39(22)</td>
</tr>
<tr>
<td>MIROC</td>
<td>MIROC5</td>
<td>Model for Interdisciplinary Research on Climate, version 5</td>
<td>Atmosphere and Ocean Research Institute (Tokyo, Japan)</td>
<td>T127</td>
<td>56(17)</td>
</tr>
<tr>
<td>MOHC</td>
<td>HadGEM2-CC</td>
<td>Hadley Centre Global Environmental Model, version 2 (Carbon Cycle)</td>
<td>Met Office Hadley Centre (United Kingdom)</td>
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<td>60(37)</td>
</tr>
<tr>
<td>MPI</td>
<td>MPI-ESM-MR</td>
<td>Max Planck Institute Earth System Model, medium resolution</td>
<td>Max Planck Institute for Meteorology (Hamburg, Germany)</td>
<td>T63</td>
<td>95(47)</td>
</tr>
<tr>
<td>MRI</td>
<td>MRI-CGCM3</td>
<td>Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3</td>
<td>Meteorological Research Institute (Japan)</td>
<td>T159</td>
<td>48(20)</td>
</tr>
<tr>
<td>NCAR</td>
<td>CCSM4</td>
<td>Community Climate System Model, version 4.0</td>
<td>National Center for Atmospheric Research (Boulder, Colorado)</td>
<td>0.9° × 1.25°</td>
<td>27(13)</td>
</tr>
<tr>
<td>NCC</td>
<td>NorESM1-M</td>
<td>Norwegian Earth System Model, version 1 (intermediate resolution)</td>
<td>Norwegian Climate Centre</td>
<td>0.9° × 1.25°</td>
<td>26(13)</td>
</tr>
<tr>
<td>NOAA</td>
<td>GFDL-ESM2M</td>
<td>Geophysical Fluid Dynamics Laboratory Earth System Model with MOM4 ocean component (ESM2M)</td>
<td>National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory (Princeton, New Jersey)</td>
<td>2° × 2.5°</td>
<td>24(5)</td>
</tr>
</tbody>
</table>
former is referred to as the twentieth-century experiment with all forcings, and the results for it can be statistically compared with the analysis of the twentieth-century observations. Here, we use the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005), with the full resolution of 1.125° (Gaussian grid N80) for the period 1958–2001. The last 44 years (2056–99) of the high greenhouse gas emission (RCP8.5) scenario runs are analyzed to compare the future projection with the simulation of the current climate. For a number of models (CAN, IPSL, MIROC, MOHC, and MPI), three ensembles have been downloaded for each experiment. From these it has been found that the variability in blocking frequencies between different runs of the same model is small. Therefore, the results displayed for these centers will be based on a single run, as for the remaining centers.

Before describing the methodology, it is noted that the original diagnostic method as pioneered in PH03 and developed further in Tyrlis and Hoskins (2008a,b), Berrisford et al. (2007), and in particular in Masato et al. (2012, 2013) was based on the potential temperature \( \theta \) on the dynamical tropopause as defined by the 2-PVU potential vorticity (PV) surface (PV2; Hoskins et al. 1985). However, this variable was not included as first priority in the guidelines of the CMIP5 project. Because of this it was decided to test the same methodology for a blocking diagnostic applied to the geopotential height \( Z \) field, both at 250 hPa (Z250) and 500 hPa (Z500), the former being close to the tropopause at mid and high latitudes. The blocking climatology for the winter season [December–February (DJF)] has been computed for the ERA-40 period for both Z250 and Z500, as well as for \( \theta \) on PV2. The agreement between \( \theta \) on PV2 and Z250, in terms of the geographical pattern of blocking frequency and the characteristics of blocking itself, was very good but because of the smoother nature of the geopotential field the blocking frequency obtained with Z250 was on average about \( \frac{2}{3} \) that obtained with \( \theta \) on PV2. With the weaker westerlies at the 500-hPa level it is found that for Z500 the climatology of analyzed blocking frequency increases back to that for \( \theta \) on PV2. It is also noted that, with one exception,\(^1\) the behavior in blocking frequency and location and its response for the twenty-first century is nearly barotropic. Further, Z500 is also the field that has historically been used to calculate blocking frequency. Therefore, it was decided to apply the PH03 methodology to Z500 for the analysis in this paper. However, reference will be made to the results associated with Z250.

These findings confirm those in Barnes et al. (2012) where they concluded that blocking was coherently identified independently of the field used (they used \( \theta \) on PV2, Z500, and the 500-hPa zonal wind field \( \vec{u} \)). However, other studies (e.g., PH03; Barriopedro et al. 2010a) have already noted that the usage of different blocking diagnostic methodologies can lead to somewhat different results. Our methodology seeks a reversal of the meridional gradient of the geopotential averaged over a specified latitudinal range. It is symmetrical in the sense that it seeks to identify both poleward blocking highs and persistent equatorward cutoff lows, placing no criterion on whether the westerlies are diverted to the north or south. In the appendix, the differences of the present methodology from those in some other studies are discussed and the advantages are highlighted.

b. Methodology

The diagnostic method follows Masato et al. (2012) for a 1D analysis and Masato et al. (2013) for a 2D analysis; details can be found in these papers. Here, we list the most important steps, which are applied in this study in the same manner as the daily mean Z500 field. The resolution of the 12 models is not identical; therefore each geopotential field has been interpolated onto a 4.5° \( \times \) 1.5° longitude–latitude grid. A finer grid in longitude (1.5° \( \times \) 1.5°) has also been used for the MOHC model to test the sensitivity to this. No substantial differences were detected either for the frequency or for the geographical location of blocking. Such finer resolution may be required in a model to simulate blocking but is not necessary for its diagnostic.

The integrals

\[
Z_i' = \frac{2}{\Delta \phi} \int_{\phi_{i-1}}^{\phi_i} Z_i \, d\phi; \quad Z_i'' = \frac{2}{\Delta \phi} \int_{\phi_{i-1}}^{\phi_i} Z_i \, d\phi
\]

have been calculated at every point in longitude, with \( \Delta \phi = 30^\circ \) and using 10 grid points (15°) in latitude for the two sectors (northern and southern). The blocking index \( B \) has been defined as \( B_i = Z_i' - Z_i'' \). Therefore, a positive \( B \) is associated with a large-scale reversal of the meridional gradient of geopotential, with higher pressure on average to the north and lower pressure on average to the south.

The base latitude \( \phi_0 \) in Masato et al. (2012) was calculated as a function of longitude only. Following PH03 this central blocking latitude (CBL) was derived as the maximum of the spatially smoothed mean synoptic frequency transient eddy kinetic energy (TEKE). The occurrence of blocking is therefore diagnosed at the latitude

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1 MOHC returns a much higher blocking frequency for Z500, in particular over the midlatitudes. This is translated into a strongly reduced bias at this level if compared to Z250, in particular for the European winter region.
of the storm-track axis. In the 2D approach introduced in Berrisford et al. (2007) and developed in Masato et al. (2013), \( \phi_0 \) is allowed to vary within the latitude band 40°–70°N.

In PH03, the CBL was derived from the annual TEKE, but here it is calculated separately for each season, following Barnes et al. (2012). With the ERA-40 reanalysis, the Northern Hemisphere CBL in winter over the oceans is located up to 5° south of the annual values (see, e.g., Fig. 4 in their paper), whereas the summer CBL over land is shifted north by 5°–10°. It has been found that this seasonal variation can be even more exaggerated for some models. Therefore, as the real value of the 1D approach is the identification of those events that most directly interfere with the storm track, winter (DJF) and summer [June–August (JJA)] CBLs are calculated for each of the models considered and used for that model and for each of the periods analyzed. One could also argue that the use of a time-mean seasonal CBL is not ideal for a future scenario where the storm tracks are certainly not stationary. However, it will be shown (see Figs. 4c and 8c) that the CBL zonal variations are larger than the trend in the CBL poleward shift, and this is even truer for the intermodel difference in the CBL response.

Different techniques are used to identify blocking events in the 1D and 2D methodologies. For the 1D methodology two more definitions were included: sector blocking (SB), which accounts for the zonal extent and near stationarity of blocking, and sector blocking episode (SBE), which accounts for time persistence [for all details, see Masato et al. (2012)]. For the 2D methodology a tracking algorithm was employed to follow in time the relative maxima of the 2D \( B \) index after onset (the first day \( B \) becomes positive in a given region), with restrictions placed on the allowable movement between individual days and in total from the onset location according to the following criteria:

1) Local positive \( B \) maxima (now identified as blocking centers) are detected at each day from the 2D \( B \) field, considering only positive values of the index (i.e., where the meridional gradient is reversed).

2) If a maximum detected at day \( n + 1 \) is within a 27° (latitude) \( \times 36° \) (longitude) box, centered at the blocking center of day \( n \), then such a maximum is interpreted as the continuation of the blocking event. Otherwise, it is defined as the beginning of a new one. If two or more maxima meet such a condition, the one closest to the blocking center at day \( n \) is chosen.

3) An event is also defined to finish when there is no positive continuation maximum within a box 50% greater in both latitude and longitude than that in point 2, centered on the position of the onset maximum.

4) If conditions 2 and 3 are satisfied, then the value of \( B \) associated with the blocking center is retained from the two-dimensional fields and stored as a function of time.

Therefore, the 1D approach returns a time series for \( B \), SB, and SBE as a function of longitude, and blocking is identified with positive values of the \( B \) index. The 2D approach stores each blocking event (i.e., episodes when a positive relative maximum of \( B \) is detected) as a function of time and geographical location, and for each day all grid points exhibiting a positive \( B \) index and adjacent to the relative maximum are labeled as “blocked.” For both methods, the frequency of blocking is calculated for each grid point and normalized by the total number of days for the season considered. Both the methods retain the blocking events lasting more than 5 days only. For the 1D approach, the results of this study will be presented based only on the SBE index. While the 2D approach is more comprehensive and not sensitive to the CBL choice, the 1D methodology only measures classical midlatitude blocking and moves along the storm track. Hence, a change in blocking within the 1D approach is usually due to both a net trend in its frequency of occurrence and a change in the storm-track location. On the other hand, the advantage of the 1D approach is the ability to summarize blocking characteristics in many models in only one figure.

3. Winter blocking

a. Twentieth century

Figure 1 shows the blocking daily frequency results for the twentieth century as derived from the 2D approach. The three top panels illustrate respectively, the blocking frequency for ERA-40 and the multimodel mean, and also the intermodel standard deviation. The color shading indicates the difference in frequency between the multimodel mean and ERA-40, with blue indicating deficit and red surplus. The observed blocking climatology shows three main centers of action, one over Europe and two other high-latitude blocking regions in the northwest Atlantic Ocean and the north northwest Pacific Ocean. The distribution of the blocking frequency is almost identical to that in Masato et al. (2013; see our Fig. 2), where the same methodology has been employed but applied to a different variable (\( \theta \) on PV2 instead of Z500) and is very similar to other studies that have used the reversal of the meridional gradient on the dynamical tropopause (e.g., Woollings et al. 2008).
FIG. 1. (top) The 2D daily frequency of blocking (expressed in percentages; see section 2b for more details) during winter for ERA-40, the multimodel mean, and the intermodel standard deviation. The color shading represents the difference between the multimodel mean and the reanalysis. (bottom) The 2D daily blocking frequency for all the models considered (see Table 1 for details). Contours are every 0.05. The color shading represents the difference between each model and the reanalysis.
The blocking signal over the Euro-Atlantic sector is in accordance with previous studies (such as Barriopedro et al. 2010a), where a semi-bidimensional approach was adopted but very different from some others, such as Croci-Maspoli et al. (2007). This difference is due to a different approach [the reversal method versus the anomaly method; see Barriopedro et al. (2010a) for a summary of the two methods] and also to the different tracking method employed. Here, a maximum distance from the onset location has been imposed, so that the blocking event is forced to be a quasi-stationary feature.

As seen in Fig. 1, the greatest model bias is found over Europe, where the multimodel blocking frequency is less than half of that in ERA-40 (0.08 versus 0.18 daily blocking frequency). The intermodel standard deviation over Europe is around 0.05. This is about half of the mean bias, which suggests that most models are deficient in their representation of blocking over Europe. The results for each center shown in Fig. 1 confirm this. Three of the models (MIROC, MOHC, and MPI) have a European blocking maximum near the correct location and with frequencies greater than 0.15. EC-EARTH exhibits the correct location but with a frequency of 0.12. European blocking is not represented correctly or it is not represented at all in the other models.

The models generally represent high-latitude blocking better. The underestimate of the frequency is replaced by an average westward shift, in particular for the Pacific sector. On the other hand the intermodel standard deviation is high, indicating a diverse behavior. IPSL and MIROC overrepresent blocking over the entire Pacific basin, whereas CAN and EC-EARTH exhibit a substantial deficit on the eastern flank. The others show rather complex biases, usually associated with zonal (e.g., BCC, MOHC, and MPI) and/or meridional shifts (e.g., CNRM and NOAA). Atlantic blocking is overall underestimated on its southern edge, but at least two models (MOHC and NOAA) stand out from the others and describe it well. The majority of models underestimate its frequency by more than 0.1, but some (CNRM, IPSL, MIROC, and MPI) overestimate it to varying extents. The fact that some models overestimate blocking frequency is inconsistent with the basic idea that model errors arise primarily from resolution limitations, which prevent them from resolving blocking and wave-breaking processes.

The winter 1D blocking daily frequency results are given in Fig. 2. As in blocking frequency results given by the Tibaldi–Molteni (TM) index (Tibaldi and Molteni 1990), the Euro-Atlantic and Pacific peaks are found. Unlike the 2D approach, here the Pacific frequency is lower than its European counterpart as the winter CBL is located at the southern flank of the high-latitude blocking. If a fixed 60°N latitude were used for the CBL, then a much higher 1D signal would appear over the Pacific region.

Figure 2a shows the substantial blocking frequency deficit in the European region for the multimodel mean. The mean maximum frequency in the models is 0.07 compared with 0.18 in ERA-40, values identical to those found with the 2D index. The differences of the individual models from the model mean are summarized in Fig. 2b. Only two models (MIROC and MOHC) are able to capture the midlatitude signal over Europe, with EC-EARTH and MPI also indicating this feature. However, the MPI performance is partially compromised by an equatorward bias of its CBL over eastern Europe (Fig. 2c). The eastward shift of blocking (to 40°–80°E)
affecting the NCAR and NCC centers is mainly due to the positive bias in frequency well visible within the 2D signal (see Fig. 1). In contrast, the multimodel-mean frequency for the Pacific peak in Fig. 2a is greater than that in ERA-40 by around 0.02. The apparent contradiction with the 2D approach is because the highest peak of the 1D blocking frequency is centered at around 140°W, exactly where a positive bias is observed for the 2D blocking signal. The individual model errors in the Pacific region (Fig. 2b) vary because of the errors in both the 2D frequency and in the CBL (Fig. 2c). In particular, the CBL location relative position from the 2D blocking region translates into an over- or under-estimate of the 1D blocking index if the CBL moves closer to or away from the 2D signal.

b. Twenty-first century

Blocking results for the twenty-first century are summarized in Fig. 3. The top panels illustrate, respectively, the multimodel mean of daily blocking frequency for the twentieth century, that for the twenty-first century with the twenty-first minus the twentieth-century difference shown by color shading, and the intermodel standard deviation of this difference, also shown in shading. A slight decrease is apparent over Europe and the Atlantic (0.02–0.03). The proportional decrease is similar to the 15%–30% value suggested by some CMIP3 bodies of research (Barnes et al. 2012; Sillmann and Croci-Maspoli 2009). It is not known to what extent these blocking changes might be affected by the large biases shown in Figs. 1 and 2a, and the intermodel standard deviation of these changes is seen to be large. The best performing models for European blocking do not completely agree on the twenty-first-century prediction under a strong CO₂ emission scenario. EC-EARTH and MPI show an eastward shift (it is noted, however, that EC-EARTH and MPI have a common history and so they may not be completely independent), while MIROC and MOHC exhibit a decrease of blocking frequency over central and western Europe equal to and greater than 0.05, respectively. More generally, 7 models out of 12 predict a decrease in blocking over Europe, while the others do not exhibit significant trends.

The Pacific high-latitude blocking trend shows overall a poleward shift. However, again, the standard deviation of the change in this region is very high. Four models out of 12 (CAN, CNRM, EC-EARTH, and MRI) show an overall blocking increase, in particular over the central and east Pacific, whereas for the remaining eight the response is more diverse. BCC, IPSL, MPI, and, to a minor extent, MOHC and NCAR, exhibit an eastward and poleward shift, whereas MIROC shows the opposite trend. NCC and NOAA predict a decreased blocking frequency over the northeast and northwest Pacific, respectively.

High-latitude blocking over the Atlantic Ocean shows on average a small decrease. However, similar to the Pacific region, the twenty-first-century prediction substantially varies from model to model. BCC, CNRM, and IPSL show a reduction (i.e., difference from their climatology in absolute values of frequency) by more than 0.05, whereas little change is observed for CAN, EC-EARTH, MPI, NCAR, NCC, and NOAA. MOHC is the only model showing a net increase in high-latitude Atlantic blocking frequency.

The 1D index for the multimodel means (Fig. 4a) clearly shows a projected decrease in the European blocking frequency by about 0.02. This is consistent with the 2D results. However, Fig. 4a also emphasizes that no decrease is projected for the eastern part of this blocking region. This behavior is present in most of the models as is seen in Fig. 4b. The multimodel mean for the east Pacific region shows little change, though there is a spread in the models (Fig. 4b). The behavior in the individual models is strongly influenced by the relative location of the CBL: a poleward shift in the CBL tends to give higher blocking frequencies. However, the average CBL does not move significantly poleward for a warming climate. The mean change in 1D blocking frequency is therefore not strongly influenced by this and can be directly compared with that given by the 2D index.

4. Summer blocking

a. Twentieth century

The 2D blocking frequency climatology for the summer season is displayed in Fig. 5; the top panels show (from left to right) the ERA-40 and the multimodel-mean blocking frequency and the intermodel standard deviation. As in Fig. 1, the color shading represents the difference between the model mean and ERA-40. In this case, a comparison with previous climatologies of blocking is not possible as the 2D blocking literature covers the winter season only. In this respect, it is useful to recall that this blocking index does not impose any further condition on the presence of westerlies to the north of the blocking ridge (see the appendix for more details). This results in a blocking climatology with very high-frequency values at higher latitudes, in particular during the summer period, which is associated with the poleward movement of the jet stream.

The Atlantic and Pacific high-latitude blocking maxima are somewhat reduced and shifted northeast compared with winter. They are now linked by a collar of
FIG. 3. (top) The 2D daily frequency of blocking (expressed in percentages; see section 2b for more details) during winter for the multimodel mean (twentieth and twenty-first century) and the intermodel standard deviation of their difference (twenty-first — twentieth century). The color shading represents the difference between the multimodel means (twenty-first — twentieth century). (bottom) The 2D daily blocking frequency by the end of the twenty-first century for all the models considered (see Table 1 for details). Contours are every 0.05. The color shading represents the difference between the twenty-first- and the twentieth-century frequencies for each of the models.
relatively high blocking frequency that includes a significantly northeast shifted European blocking maximum and an additional Russian maximum. The model mean generally captures the differences from winter. However, eastern European and Russian blocking is too weak and oceanic blocking is too strong. In the Atlantic this is the case over the whole region, whereas in the Pacific the error is mainly over the extreme subpolar region. In proportion to the amount of blocking, there is considerable intermodel variability in each of the regions.

Looking at the individual models, the best representation of blocking frequency in the Euro-Atlantic sector is perhaps that in CAN, EC-EARTH, and NCAR. The maximum in frequency is 0.16–0.17 in ERA-40 and also in EC-EARTH and NCAR, with slightly smaller values for CAN (0.1 and 0.15 respectively over the Atlantic and Europe). The Asian maximum is well represented only by IPSL and NCAR. The latter is also the model with the smallest bias for the entire Northern Hemisphere. The representation of Pacific blocking varies widely with only NCAR showing small errors. All the other centers either overestimate (CNRM, IPSL, MIROC, MOHC, MRI, and NOAA) or underestimate (BCC, CAN, EC-EARTH, and NCC) blocking frequency, with the only exception being MPI, which exhibits a slight poleward shift.

The 1D ERA-40 blocking index for summer (Fig. 6a) picks up the east European maximum, but the values are smaller elsewhere as the storm track/CBL is on the southern flank of the Russian, Pacific, and Atlantic maxima. There is an overall tendency for models to overestimate the Atlantic signal (80°W–0°), with an opposite behavior for the European and Asian region (0°–100°E). In particular, the negative bias for the Eurasian continent is overall around 0.05, consistent with the 2D maps of Fig. 5. The 1D blocking surplus over the Atlantic is less than that seen in the 2D plots. This is due to the CBL location for this sector, which spans from 50° to 60°N (see the dashed black line in Fig. 6c, which represents the CBL for ERA-40), whereas the maximum blocking activity is located farther north, at around 65°N.

The 1D ERA-40 Pacific blocking maximum (Fig. 6a) is similar to that seen in other studies (e.g., Barnes et al. 2012). Almost all the models overestimate it, some by a large amount. The error is much less apparent in the 2D approach (Fig. 5). It is necessary to analyze the CBL biases and combine them with the 2D blocking errors to understand such a discrepancy. Three of the six models, which are strongly characterized by a positive bias here (CAN, NCAR, and NCC), are associated with a large poleward displacement of the CBL (see Fig. 6c), which causes the 1D algorithm to seek for blocking in a region where it is very active. For CNRM, MIROC, and MOHC the overestimate seen in the 2D blocking frequency is dominant.

b. Twenty-first century

Figure 7 displays the twenty-first-century summer 2D blocking frequency projections. The top panels give, respectively, the multimodel mean for the twentieth century and the twenty-first century with the difference shown by color shading, and the intermodel standard deviation of this difference, also shown in shading. The reduction in blocking frequency over Europe and enhancement over Russia imply an eastward shift with even slightly enhanced intensity. There is a relatively high model spread for this result over Europe but
less over Russia. The high-latitude blocking in the Pacific shows a small decrease in the mean but a large spread and a marked decrease in the Atlantic with a smaller spread.

The three models that produced the most accurate Eurasian blocking frequencies for the summer seasons all show an increased blocking frequency over Asia and a reduction either over the western North Atlantic (CAN and NCAR) or the eastern North Atlantic (EC-EARTH). The rest of the models, with the exception of BCC, exhibit a general reduction in blocking.
frequency over the Atlantic. NCC predicts a much larger increase in blocking frequency over Asia than the other models. There is disagreement among the models about the twenty-first-century projected changes for the Pacific region, with many of them exhibiting a localized decrease with strong decreases for MRI, IPSL, and NOAA, whereas CAN and NCC show increase.

The model-mean 1D blocking frequency change for summer (Fig. 8a) indicates an eastward shift and enhancement of European blocking. In fact, there is an enhancement everywhere except in the eastern ocean basins. This is in contrast to the CMIP3 results of Barnes et al. (2012). The European behavior seen in the 1D index somewhat reflects that seen in the 2D index (Fig. 7). However, the general increase reflects the mean poleward shift by about 5° of the storm track and CBL toward the region of higher blocking (Fig. 8c). In the Atlantic, this compensates the decrease in blocking, and in the Pacific it leads to a net increase. The wide range of the twentieth- to twenty-first-century changes in the individual models (Fig. 8b), along with the wide discrepancies of their twentieth century results from ERA-40, suggests that care must be exercised in interpreting the results for summer.

5. Summary and conclusions

The representation of Northern Hemisphere blocking for the twentieth century and its projection for the twenty-first century under a strong CO2 emission scenario have been analyzed using the CMIP5 project models of 12 different centers. An index based on the large-scale reversal of the meridional gradient in Z500 has been used. A 1D and a 2D approach have been adopted, following the analysis of Masato et al. (2012, 2013). The 1D technique identifies blocking that is directly interfering with the storm-track progression of weather systems and is primarily found in midlatitudes. In addition to these events identified by the 1D index, the 2D method also detects events at higher latitudes, where blocking is generally located on the northern flank of the jet stream over the Pacific and Atlantic Ocean. The winter and summer seasons have been analyzed, and the most important findings are summarized as follows:

- Wintertime blocking frequency is heavily underestimated by almost all models. This is particularly the case for the Euro-Atlantic sector, where the mean deficit is greater than ½ of the total daily frequency, in accordance with CMIP3 results (e.g., D’Andrea et al. 1998; Scaife et al. 2010).
- Winter blocking is observed to decrease by the end of the twenty-first century over Europe by 0.02–0.04 in daily frequency, which corresponds to a 30% decrease in blocked days. However, the eastern European blocking frequency is not decreased. High-latitude blocking over the Pacific exhibits an overall poleward shift, although the behavior is not coherent throughout all the models. Similar statements can be made for the high-latitude signal over the Atlantic, although a smaller decrease (0.02 in frequency corresponding to a 10%–15% decrease in blocked days) is present there for the multimodel mean.
- The smaller trend observed for the Atlantic sector (as opposed to the European strong decrease) is in accordance with some recent studies where it is suggested that the better resolved stratosphere of some CMIP5 models might play an important role for the negative Arctic Oscillation (itself very closely related to blocking) shift relative to models with a poor stratospheric representation (e.g., Karpechko and Manzini 2012).
- Summertime daily blocking frequency over the oceans is on average overestimated (0.1 surplus over the
Atlantic, between 0.05 and 0.1 over the subpolar North Pacific), while on average Eurasian blocking is underestimated with a 0.05–0.08 deficit.

- The blocking frequency projections for summer show an overall poleward shift along with a decrease in magnitude over Europe, a large decrease (corresponding to 40% less blocked days) over the high-latitude Atlantic, and a decrease in the high-latitude east Pacific. However, the European decrease is accompanied by an increase on its eastern flank, leading to an eastward
This is more marked but similar to the change seen in winter in this region. The summertime increase in the eastern Europe–western Russia region corresponds to about a 35% increase in blocked days there. Interestingly, this is located just downstream of the region where blocking led to an intense heat wave during the summer of 2010 (Dole et al. 2011) and influenced the occurrence of the Pakistan floods (Hoskins 2013).

The poleward shift in the storm track in summer may mean that even slightly reduced blocking at high latitudes could result in a larger impact on the eastward movement of storm-track systems.

The 1D and 2D approaches return a complete picture of blocking representation in the CMIP5 models, adding complementary information for the mid- and high-latitude events. In this regard, it is observed that unlike other diagnostics (e.g., the Tibaldi–Molteni index; see the appendix for more details), the approach used here tends to pick up a high fraction of the large-scale reversal at high latitudes, which is favored by a very weak meridional gradient of temperature and pressure in those regions. This is also why the 1D method is important, particularly during the winter season, in order to isolate the midlatitude blocking signature, which is bound to the storm-track activity.

It should be noted that the results have been shown here for the methodology applied to the 500-hPa height field. However, the methodology has been repeated for the same field at 250 hPa and the conclusions highlighted here also apply to a good approximation at that level. The qualitative and even quantitative similarity of ERA-40 results based on these height fields to those based on potential temperature on the dynamical tropopause is suggestive that similar conclusions would also have been made if that field had been available for analysis.

It has often been said that a model’s performance in predicting blocking might be correlated with its resolution (e.g., Matsueda 2009), as it tends to have smaller mean state biases, and this may be the primary cause of improved blocking frequency. In Table 1, the horizontal and vertical resolutions of the atmosphere are listed for all the models considered. It is seen that in general the best performing models (e.g., EC-EARTH, MIROC, MOHC over Europe in winter, and NCAR in summer) tend to have the finer resolution. However, some exceptions are also noted: MPI, which performs quite well during winter, has only a T63 truncation (roughly corresponding to 1.9°) but a very well-resolved stratosphere, while NCAR is characterized by a low vertical resolution. On the other hand, the MRI resolution is quite high nevertheless, the model is not among the best in simulating blocking.

It is also of interest that the models giving the most accurate simulation of blocking frequency in winter and summer were different. This might indicate that the difficulty in capturing local wave-breaking processes is not the prominent factor. In a recent study, Scaife et al. (2011) found that the ocean resolution has a much stronger impact on European blocking than the atmospheric resolution. Anstey et al. (2013) also found that the vertical resolution seems to have the strongest impact for improving the high-latitude blocking signal in the CMIP5 models. All these findings suggest that there is no unique way to improve the representation of blocking, and further analyses will be necessary to learn more about this issue.

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APPENDIX

Blocking Indices: A Comparison

In this appendix the main differences between the TM index and the index employed in this study are clarified. This aids the comparison among the previous CMIP3 results, CMIP5 results given elsewhere, and those described here.

The PH03 index is based on searching for reversals of the meridional gradient of potential temperature on the PV2 surface. This field is used because of its dynamical significance and conservative properties. Since it is not available in the CMIP5 archive, the same index has been applied here to the height fields at both 250 hPa (Z250) and 500 hPa (Z500). When applied to Z500, the concept is similar to that embodied in the Tibaldi and Molteni index (for further details see Tibaldi and Molteni 1990) but with some important differences. These differences still hold for adapted versions of the TM index, calculated as the meridional integral of the zonal wind field $u$ [see Scaife et al. (2010) and Barnes et al. (2012) for a 2D and 1D framework, respectively].

The most fundamental difference between the methodology used here and that in TM is that in the former there is equal consideration of the occurrence of poleward negative PV anomalies (high Z) and equatorward positive PV anomalies (low Z). Thus blocking highs and cutoff lows are both considered as blocking the latitude at which the associated easterlies occur. There is no criterion on the westerly winds that can be diverted to north or south or both. This contrasts with the TM method in which, having found a region of easterly winds, there is a second requirement of strong westerly winds on the poleward side. Consequently, the focus is on only the blocking high.

When used in a 1D version, the TM index is usually applied at a constant latitude, whereas the 1D version used in this paper is applied at a latitude that corresponds to the climatological storm track at that longitude, consistent with seeking blocking of the storms. When applied in 2D, the value of the TM index tends to be recorded at the latitude of the maximum in the blocking high (Scaife et al. 2010). However, in 2D versions used in this paper (following Berrisford et al. 2007) it is recorded at the latitude of the maximum reversed meridional gradient, corresponding to the implied maximum easterly winds and consistent with the symmetry of the methodology.

With the 2D version used here, high-latitude blocking is identified in the Southern Hemisphere (similar to Berrisford et al. 2007) and also in the North Atlantic and North Pacific (similar to Woollings et al. 2008; Masato et al. 2013) on the poleward flanks of the jet streams. These high-latitude blocks are generally associated with an equatorward shift of the jet and with negative phase of the North Atlantic Oscillation and the west Pacific pattern in the Atlantic and Pacific, respectively. The frequencies of these high-latitude blockings are much reduced with the TM index as the poleward westerly flow criterion is much less frequently satisfied at these high latitudes.

The other more subtle difference is that TM index uses simple differences of $Z_{500}$ between two grid points to identify a region of average easterly winds. Following the methodology of PH03 originally applied to potential temperature on the PV surface, its application here to $Z_{500}$ is based on comparing integrals over a fixed latitudinal scale of $Z_{500}$ to the north and south of the base latitude and looking for higher average heights poleward than equatorward. The meridional smoothing inherent in the integrals means that local reversals in the wind tend to be counted less than they are with the TM index. Consequently, if the latter is applied to latitudes down to $20^\circ$N over the Euro-Atlantic region, then a continuous band of maximum blocking frequencies appear from the subtropical region up to western and central Europe (e.g., Davini et al. 2012). In contrast, with the PH03 index there is no subtropical maximum and European blocking is dominant in the region.

REFERENCES


