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Linking Northern Hemisphere blocking and storm track biases in the CMIP5 climate models

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The relationship between biases in Northern Hemisphere (NH) atmospheric blocking frequency and extratropical cyclone track density is investigated in 12 CMIP5 climate models to identify mechanisms underlying climate model biases and inform future model development. Biases in the Greenland blocking and summer Pacific blocking frequencies are associated with biases in the storm track latitudes while biases in winter European blocking frequency are related to the North Atlantic storm track tilt and Mediterranean cyclone density. However, biases in summer European and winter Pacific blocking appear less related with cyclone track density. Furthermore, the models with smaller biases in winter European blocking frequency have smaller biases in the cyclone density in Europe, which suggests that they are different aspects of the same bias. This is not found elsewhere in the NH. The summer North Atlantic and the North Pacific mean CMIP5 track density and blocking biases might therefore have different origins.

1. Introduction

Rapidly moving extratropical cyclones and stationary atmospheric blocking are two fundamental aspects of midlatitude atmospheric variability. Therefore, a realistic climate simulation requires both phenomena to be well represented by climate models. However, the two phenomena are linked by strong dynamical interactions [*Nakamura and Wallace*, 1993] and connections between blocking, the jet stream positions [*Woollings et al.*, 2010; *Davini et al.*, 2013] and extratropical cyclone numbers [*Trigo et al.*, 2004] have been identified in the natural variability.

Blocking events tend to maintain a deformed atmospheric large scale flow and consistently divert extratropical cyclones either to the north or to the south [*Rex*, 1950; *Woollings et al.*, 2010]. *Woollings et al.* [2008] demonstrated how the negative phase of the North Atlantic Oscillation (NAO), which is characterised by a south-shifted jet-stream regime over the Atlantic, is generally associated with the occurrence of high-latitude blocking over Greenland. The blocking in the North Pacific has also been found to be associated with large scale teleconnection patterns [*Croci-Maspoli et al.*, 2007], although the relationship appears to be weaker than in the Atlantic.

Climate models tend to underestimate the observed blocking frequency [*D'Andrea et al.*, 1998]. This tendency is still present in the latest generation of climate models participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) [*Anstey et al.*, 2013; *Masato et al.*, 2013; *Sigouin and Son*, 2013]. Moreover, recent studies have also shown that CMIP5 models are affected by biases in the representation of extratropical cyclones [*Chang et al.*, 2012; *Zappa et al.*, 2013] (see section 3 for details).

The strong dynamical interactions between blocking and cyclones may suggest that the model biases in the two phenomena are related as they are in the natural variability. However, this has not been studied before. Moreover, it is possible that biases in distinct climate processes separately affect the models representation of cyclones and blocking thus breaking the associations found in the natural variability. For example, biases in atmospheric baroclinicity, in cyclone intensification by latent heat release, and in small scale dissipation might all affect extratropical cyclones. On the other hand, there is some evidence that blocking biases may be associated with biases in the time mean jet stream [*Scaife et al.*, 2010], although the representation of the mechanisms which control blocking formation, in particular Rossby wave-breaking [*Masato et al.*, 2012] and eddy forcing [*Berckmans et al.*, 2013], may also play a role.

In this paper we will explore the extent that biases in cyclones and blocking are associated in the CMIP5 models in the NH winter and summer as they are in the natural variability. The assumption that models characterised by better blocking are also better at capturing cyclone track density will be also tested. Where this is the case, it will be argued that blocking and cyclone biases are different aspects of the same climate model bias, while, elsewhere, it will be suggested that the biases may result from distinct climate processes.

2. Data and Methods

Thirty years (1976-2005) of historical simulations from 12 CMIP5 models (see Auxiliary Material) are analysed. None of these models share the same configuration for their atmospheric components. Historical simulations refer to coupled climate model simulations forced by observed external forcing [*Taylor et al.*, 2012]. Winter (DJF) and summer (JJA) seasons are both investigated. The CMIP5 models are evaluated against ERA-Interim (ERAI) reanalysis (1980-2009) [*Simmons et al.*, 2007].

Extratropical cyclone tracks are identified using an automated cyclone tracking algorithm [*Hoskins and Hodges*, 2002]. Individual cyclones are identified as maxima in the 850 hPa vorticity smoothed to T42 resolution and their propagation tracked by minimising a cost function subject to constraints on speed and smoothness. Features propagating less than 1000 km and lasting less than 2 days are discarded to focus on mobile systems.

Atmospheric blocking is defined using the methodology introduced by *Pelly and Hoskins* [2003] and applied to the geopotential field at 500 hPa (Z500) in *Masato et al.* [2013]. Blocking is identified as a daily mean reversal of the gradient of Z500. The local reversal is calculated for a given grid point as the difference of two area integrals 15 deg in latitude, respectively to the north and to the south of the grid-point. The allowable movement of the local reversals have been also constrained in order to identify only quasi-stationary features.

3. Mean biases

The mean CMIP5 model biases have been extensively analysed in *Masato et al.* [2013] for the NH blocking and in *Zappa et al.* [2013] for the North Atlantic storm track using the same methodologies adopted here. There are slight differences in the results presented here from those in *Masato et al.* [2013] which arise from the use of a different reanalysis dataset and time period.

Fig1a,c show the climatological cyclone track density and blocking frequency in ERAI (contours) and the mean bias of the CMIP5 models (shading) for DJF. The track density bias of the CMIP5 models shows southward displaced storm tracks, in particular over the North Atlantic and the central North Pacific oceans. CMIP5 models also tend to have too few cyclones in the Norwegian and Mediterranean seas, while too many cyclones are found in the East Atlantic and central Europe. This tripolar pattern is consistent with the tendency of climate models to be too zonal over the North Atlantic in winter.

Greenland, the North Pacific and Europe are the most distinctive areas of blocking activity in ERAI. The CMIP5 models tend to underestimate the observed blocking frequency in all these regions. In particular, a large mean negative blocking frequency bias of the order of 50% is found over Europe.

The same analysis is presented in Fig 1b,d for JJA. The track density biases show an underestimation of the number of cyclones which is largest in the North Pacific. In general, CMIP5 models are better at capturing JJA blocking frequency and the mean biases are smaller compared to DJF.

The spread of the model biases is typically large and some models tend to have small track density and blocking frequency biases [*Masato et al.*, 2013; *Zappa et al.*, 2013].

4. The inter–model association between block frequency and cyclone density

To determine the extent that blocking biases are associated with storm track biases, we regress, at each grid point, the local cyclone track density against three regional blocking indices across the CMIP5 models. The regional blocking indices are obtained by area weighted averaging the blocking frequency over the boxes indicated in Fig. 1c–d, which correspond to the European, Greenland and North Pacific blocking. Spatial maps of the regression coefficients are presented in Fig. 2. For clarity, the results are only shown for the sectors relative to the blocking area.

4.1. Winter

Fig. 2a shows that models with more blocked days over Greenland tend to have smaller cyclone track density in the North-East Atlantic, and larger track density in the south-east Atlantic and in the Mediterranean. This is indicative of a weakened and southward displaced North Atlantic storm track and it is consistent with the southward displacement of the North Atlantic jet stream observed during Greenland blocking events [*Woollings et al.*, 2008]. Fig. 2c shows that models with more blocked days over Europe tend to have more cyclones in the Norwegian and Mediterranean seas and fewer cyclones in the East Atlantic and Central Europe. Such a tripolar pattern is consistent with the tendency of European blocks to divert cyclones [*Rex*, 1950] and the jet stream [*Woollings et al.*, 2010; *Davini et al.*, 2013] to either the north or the south of the block.

The relationship between biases in the North Pacific track density and the Pacific blocking frequency is also suggestive of a southward shift of the storm track but it is weaker and it has a less clear pattern than in the Atlantic (see Fig. 2e). This may be explained by the lower latitude of the Pacific storm track which may limit the association with the high latitude blocking and lead to larger influences from biases in the tropical Pacific convection.

4.2. Summer

In JJA, biases in the frequency of Greenland blocking are associated with a track density dipole between the Northern and Eastern North Atlantic (Fig. 2b). As for DJF, this is consistent with the southward shift in the jet stream expected during Greenland blocking events. A similar southward shift response, but of much larger magnitude, is also found in the Pacific. The stronger coupling between the Pacific storm track and blocking frequency in JJA is consistent with the seasonal migration of the storm track latitude, which is further northward in summer compared to winter by about 10° (see contours in Fig. 2e-f).

Of all the discussed cases, the weakest signature of inter model association between cyclone track density and blocking frequency is found for the European blocking in JJA, where the relation is largely insignificant. A possible explanation is that as summer European blocking is north–eastward displaced compared to winter it may occur too far into the continent to interact with the North Atlantic track density. The ability of climate models to simulate these two phenomena therefore appears unrelated.

5. Are small biases in blocking related to small biases in cyclone density?

In this section, we explore whether the models with small biases in blocking frequency also have small biases in cyclone track density. This is of particular interest for the European area, where the DJF mean track density bias of the models (Fig. 1a) resembles the tripolar pattern of the track density regression on European blocking (Fig. 2c), but with opposite sign. This may be consistent with the tendency of CMIP5 models to underestimate European blocking in DJF (Fig. 1c).

To test this hypothesis, the models regional track density biases over the Norwegian Sea, central Europe and the Mediterranean Sea are presented against the respective biases in the frequency of European blocking in Fig. 2a–c for DJF. These regional biases are computed by weighted area averaging over the boxes indicated in Fig. 1a, which cover the areas where the mean CMIP5 track density bias might be explained by the mean bias in European blocking frequency.

As expected, large and significant correlations are found in all regions. Furthermore, models with the largest negative biases in European blocking frequency tend to have largest track density biases in all three regions. The linear regressions of the track density biases on the European blocking biases have an intercept not significantly different from zero at the 5% level (see Fig. 3a–c). This suggests that the cyclone track density biases across Europe and the lack of European blocking are two different aspects of the same model bias in the representation of European climate. If a model has small biases in one phenomena, it is also likely to have small biases in the other.

Additional inter–model spread in the Mediterranean track density may be explained by considering the biases in Greenland blocking frequency (Fig. 3d). The correlation is large, but, in contrast to what is found for European blocking, the regression line has an intercept different from zero. Therefore, a good representation of Greenland blocking is not a sufficient condition for capturing the Mediterranean cyclone track density, whose mean bias is associated to the underestimation of European blocking frequency (Fig. 3c).

The result that blocking and track density biases are to a large extent the same bias is only found for the European blocking in DJF. Elsewhere, either the association between blocking and track density biases is small or the regression pattern does not project on the mean track density bias. The case of the North Pacific in JJA, where the blocking–track density association is large (see Fig. 2f), is explored in the auxiliary material. There we show that models with smaller biases in North Pacific blocking frequency tend to overestimate track density at high latitudes and underestimate it at lower latitudes. This suggests that other processes may be affecting the representation of North Pacific JJA track density and blocking. One possible hypothesis is that the mean negative track density bias in the South-Western North Pacific might be more related with the representation of tropical Pacific convection and the subtropical jet than with high latitude blocking.

6. Conclusions and discussion

The extent that the simulated extratropical cyclone track density and blocking frequency are associated in the NH winter (DJF) and summer (JJA) as they are in the natural variability has been explored in 12 CMIP5 models. The results show that while such associations occur in some regions and seasons, they do not occur in others.

Strong relationships between the biases in extratropical cyclone track density and blocking frequency consistent with those found in the natural variability have been detected for the European blocking in DJF, and for the North Pacific blocking in JJA. Models with more frequent North Pacific blocking in summer tend to have more southward displaced North Pacific storm track. Instead, the models with more frequent winter European blocking tend to have more cyclones in the Norwegian and Mediterranean seas, and less cyclones in Western and Central Europe.

Despite the known associations between blocking and extratropical cyclones in the natural variability, only weak relationships are found for the European blocking in JJA and for the North Pacific in DJF. These different regional and seasonal behaviours are consistent with the inland shift of European blocking in JJA and, potentially, with a larger influence of biases in the tropical Pacific convection on the North Pacific storm track in DJF.

Furthermore, we have shown that small biases in blocking frequency are not necessarily linked to small biases in the cyclone track density, supporting the idea that distinct processes may be responsible for the biases in storm track or blocking behaviour. The exception to this has been found for Europe in DJF, where the CMIP5 tendency to underestimate extratropical cyclones in the Norwegian and Mediterranean seas (i.e. the too zonal North Atlantic storm track) and to underestimate European blocking can be considered two different aspects of the same climate model bias. If models were improved to get a better representation of European blocking it can be expected that extratropical cyclone density across the whole of Europe would also improve. Finally, there is also some evidence that models with stronger cyclones upstream tend to have higher European blocking frequency (not shown), but understanding this relationship requires further investigation.

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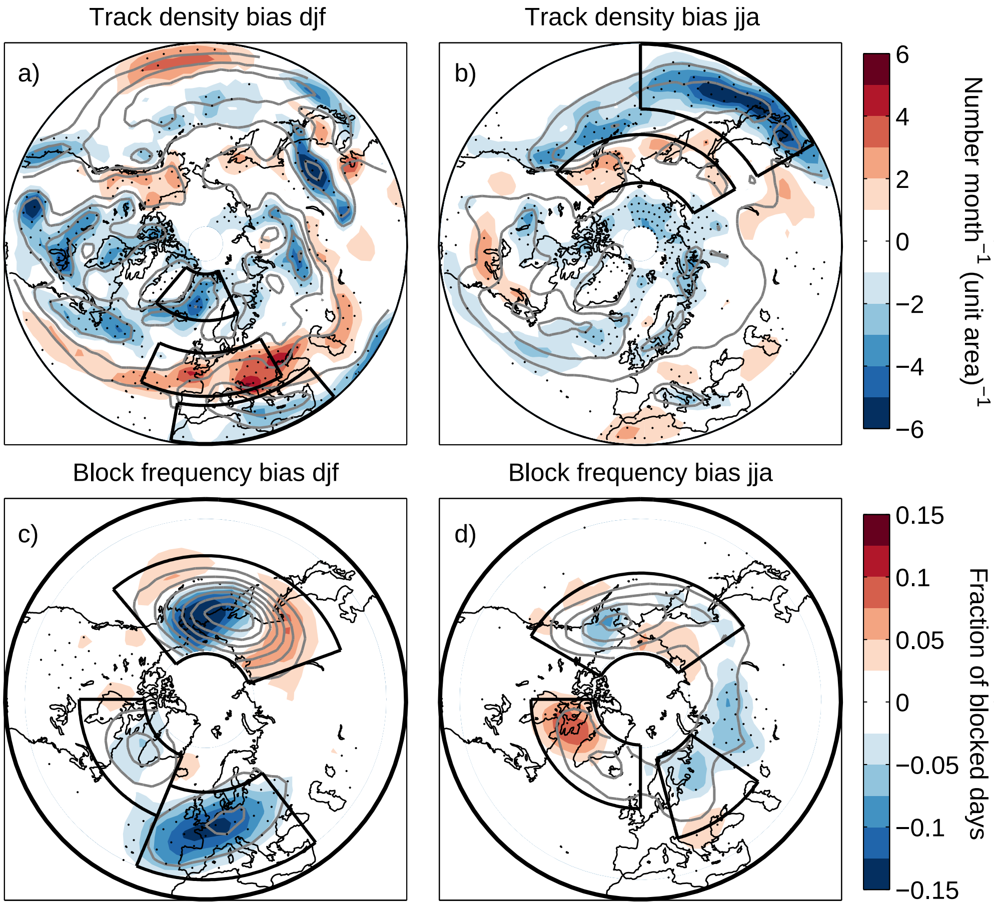

Figure 1. Multi model mean CMIP5 cyclone track density (a,b) and blocking frequency (c,d) biases (shaded) compared to ERAI. Winter (a,c) and summer (b,d) are shown. Stippling shows where the bias has the same sign in at least 80% of the models. Track density units are in number of cyclones per month per 5 degree spherical cap. Blocking frequency is expressed in fraction of blocked days. ERAI climatology is contoured, with c.i. of 5 cyclones month^{-1} for track density and 0.05 for blocking frequency. The boxes, whose boundaries are given in the supplementary materials, define the areas where the regional blocking indexes used in Fig. 2 and Fig. 3 and the track density indexes used in Fig. 3 are computed.

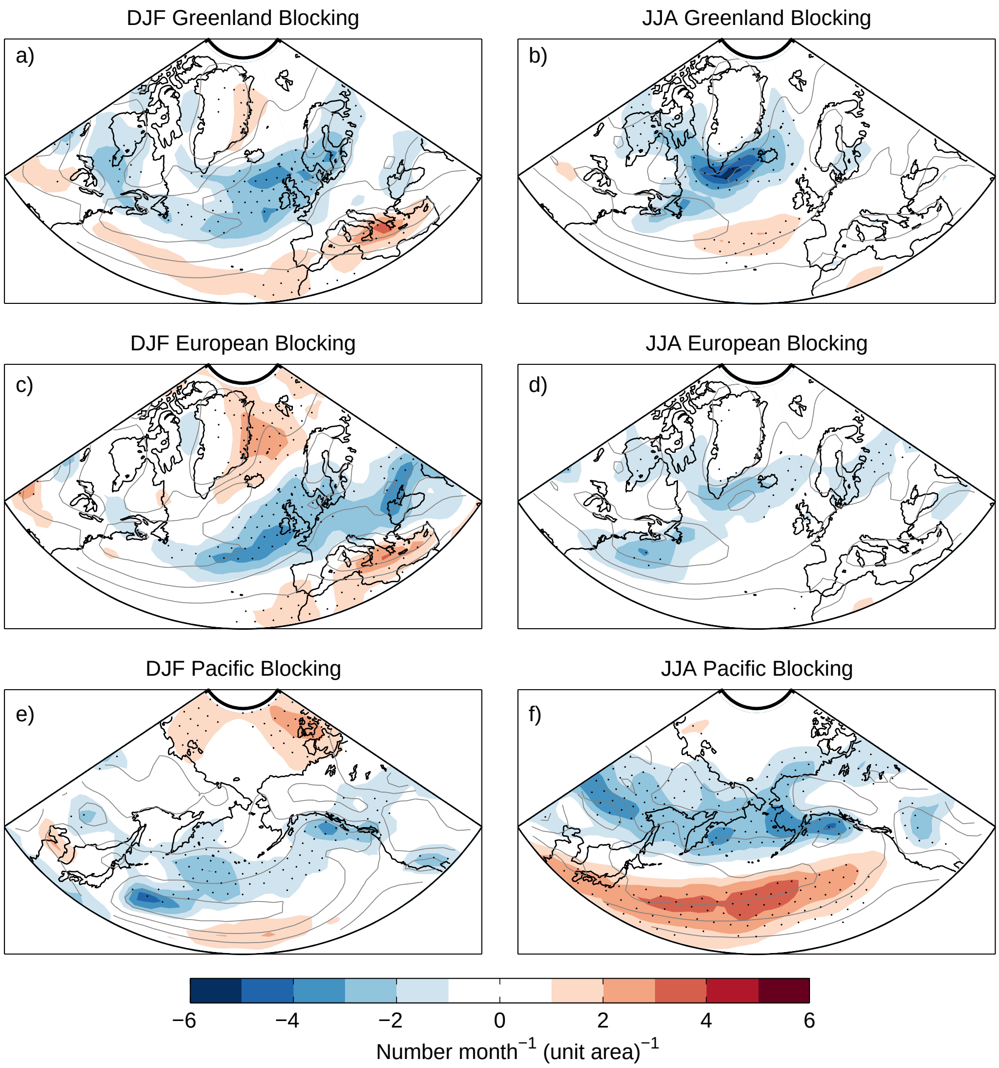

Figure 2. Inter–model regression of the cyclone track density at a given point against the Greenland (a,b), European (c,d) and North Pacific (e,f) blocking frequency. Both winter (a,c,e) and summer (b,d,f) are presented. The regression coefficients are scaled by two times the inter–model standard deviation of the blocking frequency and have units of number of cyclones per month. Grey contours give the mean CMIP5 track density, c.i. 4 cyclones/month. Stippling shows significant correlations at the 5% level according to bootstrapping.

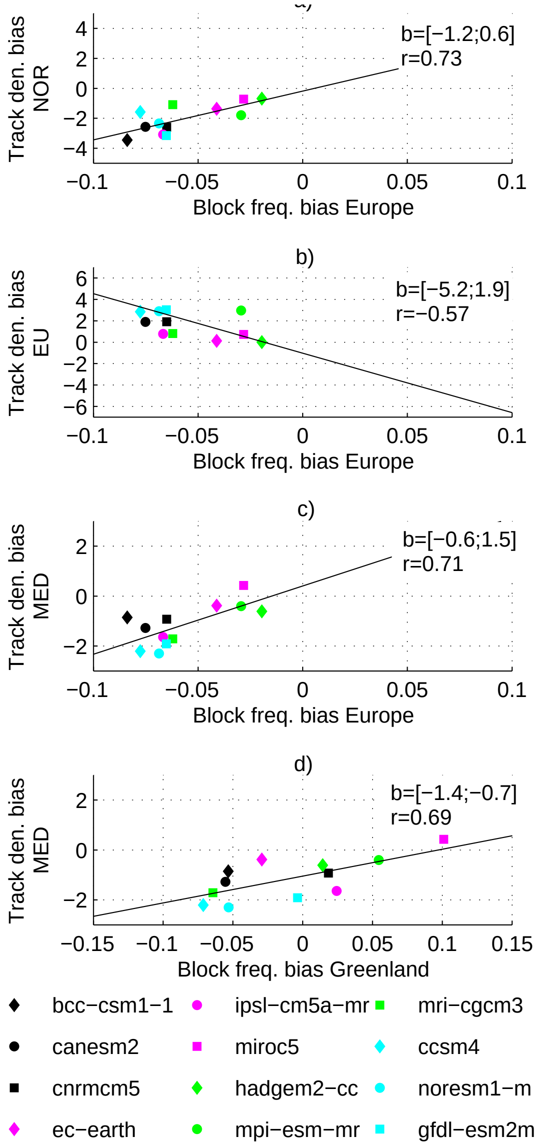

Figure 3. Scatter plots of individual model track density biases in the Norwegian sea (a), Central Europe (b) and Mediterranean sea (c) against the biases in European blocking frequency. The Mediterranean track density biases against the Greenland blocking frequency biases are shown in d). The linear correlation coefficients r and the bootstrapped 95% confidence intervals on the intercept of the linear regressions b are also shown. The correlation coefficients are all significant at the 5% level. Units are as in Fig 1.