# *Climate model biases in jet streams, blocking and storm tracks resulting from missing orographic drag*

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**Key Points:**
- CMIP5 circulation biases are consistent with the effect of missing orographic drag
- Parameterized drag reduces the Southern Annular Mode time scale

**Supporting Information:**
- Table S1

**Correspondence to:**
F. Pithan,
felix.pithan@awi.de

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# Climate model biases in jet streams, blocking and storm tracks resulting from missing orographic drag

**Felix Pithan[1], Theodore G. Shepherd[1], Giuseppe Zappa[1], and Irina Sandu[2]**

[1]Department of Meteorology, University of Reading, Reading, UK, [2]European Centre for Medium-Range Weather Forecasts, Reading, UK

**Abstract** State-of-the art climate models generally struggle to represent important features of the large-scale circulation. Common model deficiencies include an equatorward bias in the location of the midlatitude westerlies and an overly zonal orientation of the North Atlantic storm track. Orography is known to strongly affect the atmospheric circulation and is notoriously difficult to represent in coarse-resolution climate models. Yet how the representation of orography affects circulation biases in current climate models is not understood. Here we show that the effects of switching off the parameterization of drag from low-level orographic blocking in one climate model resemble the biases of the Coupled Model Intercomparison Project Phase 5 ensemble: An overly zonal wintertime North Atlantic storm track and less European blocking events, and an equatorward shift in the Southern Hemispheric jet and increase in the Southern Annular Mode time scale. This suggests that typical circulation biases in coarse-resolution climate models may be alleviated by improved parameterizations of low-level drag.

## 1. Introduction

To understand and to predict how atmospheric circulation responds to global warming is an increasingly important challenge for climate science [*Bony et al.*, 2015]. Climate models play a key role in understanding mechanisms of circulation changes, detecting externally forced signals in observations, and making projections of future changes. It is thus troubling that important features of the extratropical circulation, which is a key factor in driving extreme events including storms, heat waves, cold spells, and heavy precipitation, are substantially misrepresented in the Coupled Model Intercomparison Project Phase 5 (CMIP5) model ensemble [*Shepherd*, 2014].

Widespread model deficiencies in the extratropical circulation are an eddy-driven jet that is displaced equatorward relative to observations, especially in the Southern Hemisphere [*Bracegirdle et al.*, 2013], and a North Atlantic jet stream and storm track that is overly zonal in winter, lacking the observed southwest to northeast tilt [*Zappa et al.*, 2013]. Climate models with a stronger present-day equatorward bias in jet location tend to show a stronger poleward shift of the wintertime jet in future projections [*Kidston and Gerber*, 2010; *Bracegirdle et al.*, 2013; *Simpson and Polvani*, 2016]. *Scaife et al.* [2010] further suggest that biases in atmospheric blocking statistics depend on biases of the time mean circulation. It is therefore important to understand, and determine how to fix, the causes of these well-known circulation biases.

Circulation biases have repeatedly been shown to decrease at higher horizontal resolution [*Manabe et al.*, 1970; *Boville*, 1991]. Recent work has pointed out that at current model resolutions, such improvements largely depend on the better representation of orography at high resolutions, suggesting that a better representation of atmospheric processes such as Rossby wave breaking is, if at all, of secondary importance [*Berckmans et al.*, 2013]. This leads to the question whether improvements in parameterizations of orographic effects, which are computationally much cheaper than increased resolution, could also lead to substantial progress in modeling the extratropical circulation in current climate models.

At the typical resolution of current climate models (spanning about 50 to 150 km in midlatitudes), even the largest orographic features are only partly resolved. Parameterizations of subgrid-scale orography have long been used to represent unresolved orographic drag and thus improve circulation. Orographic gravity wave drag schemes have been developed in the 1980s and are now state of the art in climate models [*Palmer et al.*, 1986; *McFarlane*, 1987]. Gravity waves propagate upward from their source region and exert drag on the flow where they break, which often occurs at levels around or above the tropopause. However, subgrid-scale orography can also directly cause a drag on the lower troposphere due to a blocking effect on the flow. This blocking effect from unresolved mountains has been parameterized in general circulation models [*Lott and Miller*, 1997; *Gregory et al.*, 1998; *Scinocca and McFarlane*, 2000], but such schemes are only implemented in some of the CMIP5 models. Drag generated by these schemes is exerted at the altitude of the blocked flow and thus at much lower levels than orographic gravity wave drag.

Both gravity wave drag and blocking schemes are also used in numerical weather prediction models, whose forecast skills are remarkably sensitive to poorly constrained parameters that control the amount of orographic drag [*Zadra et al.*, 2003; *Sandu et al.*, 2016].

A large body of theoretical and numerical work has shown the important role of orography in shaping the jets and storm tracks [*Held*, 1983; *Brayshaw et al.*, 2009], and idealized experiments have shown how localized and even spatially homogeneous surface drag can impact the latitude of the extratropical jet [*Chen et al.*, 2007; *Ring and Plumb*, 2007; *Chen and Zurita-Gotor*, 2008]. However, the impact of the representation of orographic drag on typical circulation biases in current climate models has not been investigated in a systematic way. In the present study, we examine how the Met Office's Unified Model (UM), which has one of the most realistic representations of the wintertime North Atlantic storm track in the CMIP5 ensemble [*Zappa et al.*, 2013], responds to changes in parameterized low-level orographic drag, and to what extent the effect of orographic drag maps onto the typical CMIP5 model biases.

## 2. Model, Data, and Methods

We use the UM configuration GA6.0, corresponding to model version 8.5 with the 5A drag scheme [*Lott and Miller*, 1997; *Vosper*, 2015]. The model is run at the N96 resolution, corresponding to $1.875 \times 1.25°$. This is one of the higher, but not highest horizontal resolutions among CMIP5 models. The model top is at 85 km, and 85 levels are used in the vertical.

In the UM, drag over land is parameterized (i) in the boundary layer turbulence scheme, which uses an effective roughness length to represent orographic form drag, as (ii) low-level blocking and (iii) propagating gravity waves. The focus of our study will be on the low-level blocking scheme, which is only implemented in some of the CMIP5 models. In contrast, all state-of-the-art climate models have some representation of turbulent drag and subgrid-scale orographic gravity wave drag. While gravity waves are emitted from air parcels that are forced to ascend while moving over topographic features, low-level blocking occurs when stratification impedes an air parcel from passing over the mountain.

Flow-blocking drag is computed as

$$D_b(z) = -C_d \rho l U |U_{\mathrm{av}}|, \tag{1}$$

where $C_d$ is a tunable constant of order unity (usually set to 4 in the UM), $l$ is the mountain width seen by the flow at height $z$, $U$ the wind at height $z$, $U_{\mathrm{av}}$ a height-averaged wind, and $\rho$ is air density. The subgrid mountain height, one of the parameters controlling the depth of the blocked layer, is $h = n\sigma$, where $n$ is a tuneable constant with a standard setting of 2.5 and $\sigma$ the standard deviation of elevation within one gridbox. Full details of the implementation are given in *Vosper* [2015].

To isolate the effect of parameterized low-level drag on circulation and compare it to typical model biases, we run two UM experiments with observed sea surface temperatures following the Atmospheric Model Intercomparison Project-II prescriptions: A control run with standard settings (UM std) and a sensitivity experiment (UM noblock) in which the low-level blocking scheme is effectively switched off by setting $C_d$ in equation (1) to zero, while all other parameters are held fixed. Both runs are started in September 1981 and run until December 2012. Storm track analyses for the UM runs use data from the consecutive December–February (DJF) seasons from December 1981 through February 2012, and time means are taken over the period 1983 to 2012, such that 30 full seasons or 30 years of data are analyzed. Daily ERA-Interim data [*Dee et al.*, 2011] are used to evaluate model results. Reanalysis data are averaged over four time steps each day. CMIP5 models were selected based on data availability, and one ensemble member per model is analyzed. Biases of CMIP5 historical runs with respect to ERA-Interim are shown for the years 1979–2005 to use the maximum overlap between the data sets. To emphasize the stationary wave pattern, we remove the zonal mean from the geopotential height field at 500 hPa and only show its zonally asymmetric component z*500. We have confirmed that biases in the z*500 fields emerge in subsets of the data, so are robust.

We use annular mode indices to analyze the effect of orographic drag in different circulation regimes and on annular mode time scales. For all data sets, annular mode indices are computed as the first empirical orthogonal function of the daily, zonally averaged mean sea level pressure deseasonalized by removing a climatological annual cycle [*Gerber et al.*, 2008a]. For the Northern Hemisphere, the resulting Northern Annular Mode or Arctic Oscillation (AO) index is highly correlated with the North Atlantic Oscillation index [*Wallace*, 2000], and we use it to perform a regime analysis. We estimate the annular mode time scale using a linear fit to the logarithm of the autocorrelation function during the first *e*-folding [*Gerber et al.*, 2008a]. We analyze annular mode decorrelation time scales only for the Southern Hemisphere, where these time scales and their biases in models have been widely discussed and their dynamical relevance is unanimously accepted in the literature.

An objective cyclone tracking algorithm [*Hodges*, 1995, 1999] has been applied to characterize the North Atlantic storm track in the model simulations and in the ERA-Interim reanalysis. In particular, individual extratropical cyclones are identified every 6 h as maxima in the smoothed vorticity at 850 hPa, where the smoothing consists of filtering out all the spectral components of total wave number greater than 42 and smaller than 6. This allows us to focus on vorticity features which have the spatial scales typical of extratropical cyclones. Identified cyclones are then tracked in time by minimizing a cost function on track smoothness and speed. Only the mobile systems lasting at least 2 days and traveling 1000 km are retained for analysis. Cyclone track density [*Hodges*, 1996], which provides an estimate of the mean number of tracks passing through each region, is then used to identify the storm track position.

Blocking is diagnosed using a two-dimensional index based on daily 500 hPa geopotential heights [*Tibaldi and Molteni*, 1990; *Scherrer et al.*, 2006]. A gridpoint is defined as blocked when for at least five consecutive days, the climatological geopotential gradient south of that gridbox is reversed, while the geopotential height north of the gridbox decreases by at least 10 m$^{\circ -1}$ [*Anstey et al.*, 2013].

## 3. Results and Discussion

### 3.1. North Atlantic Jet Tilt and Storm Track and European Blocking

#### 3.1.1. Climatology and AO Variability in Reanalysis and Climate Models

The climatological DJF z*500 pattern over the North Atlantic in ERA-Interim is dominated by the standing planetary wave pattern, with a ridge extending from the Azores toward Scandinavia (Figure 1a). That ridge is weaker and more zonal in CMIP5 models than reanalysis (Figure 1d). To obtain clearer signals of the effect of low-level orographic drag in the zonally asymmetric Northern Hemisphere, we analyze days with a similar large-scale circulation using the AO index. We composite days in DJF with an index beyond $\pm 1$ standard deviation.

Compositing the zonally asymmetric component of 500 hPa geopotential heights (z*500) for the positive AO phase (Figure 1b) shows a strengthened climatological stationary wave pattern with a ridge over the Rocky Mountains, a trough over northeastern North America and a second ridge extending from the eastern Atlantic to Scandinavia. This second ridge is strongly tilted with maximum heights around 40°N over the central Atlantic and approaching 60°N over Scandinavia. The negative AO phase (Figure 1c) is characterized by a much weaker trough over North America and a much weaker ridge over the eastern North Atlantic extending into France with a secondary maximum near Iceland. The z*500 composites also reveal distinct biases of the CMIP5 models: In the positive AO phase (Figure 1e), the ridge over Europe is not tilted enough, with maximum heights at its eastern end occurring south of the Baltic rather than over Scandinavia. It also has its maximum displaced southwestward compared to reanalysis. In combination with a weaker trough over North America, this leads to smaller east-west height differences across the Atlantic in the CMIP5 ensemble mean compared to reanalysis. In the CMIP5 ensemble mean, the negative AO composite (Figure 1f) has a weakened trough compared to reanalysis and largely lacks the secondary maximum of the ridge over the eastern Atlantic near Iceland.

In the positive AO phase (Figure 2a), most cyclones over the North Atlantic travel northeastward into the Norwegian Sea, whereas in the negative phase (Figure 2b), cyclones follow a more zonal path toward Great Britain and the North Sea. This is consistent with cyclones being steered poleward by the meridional

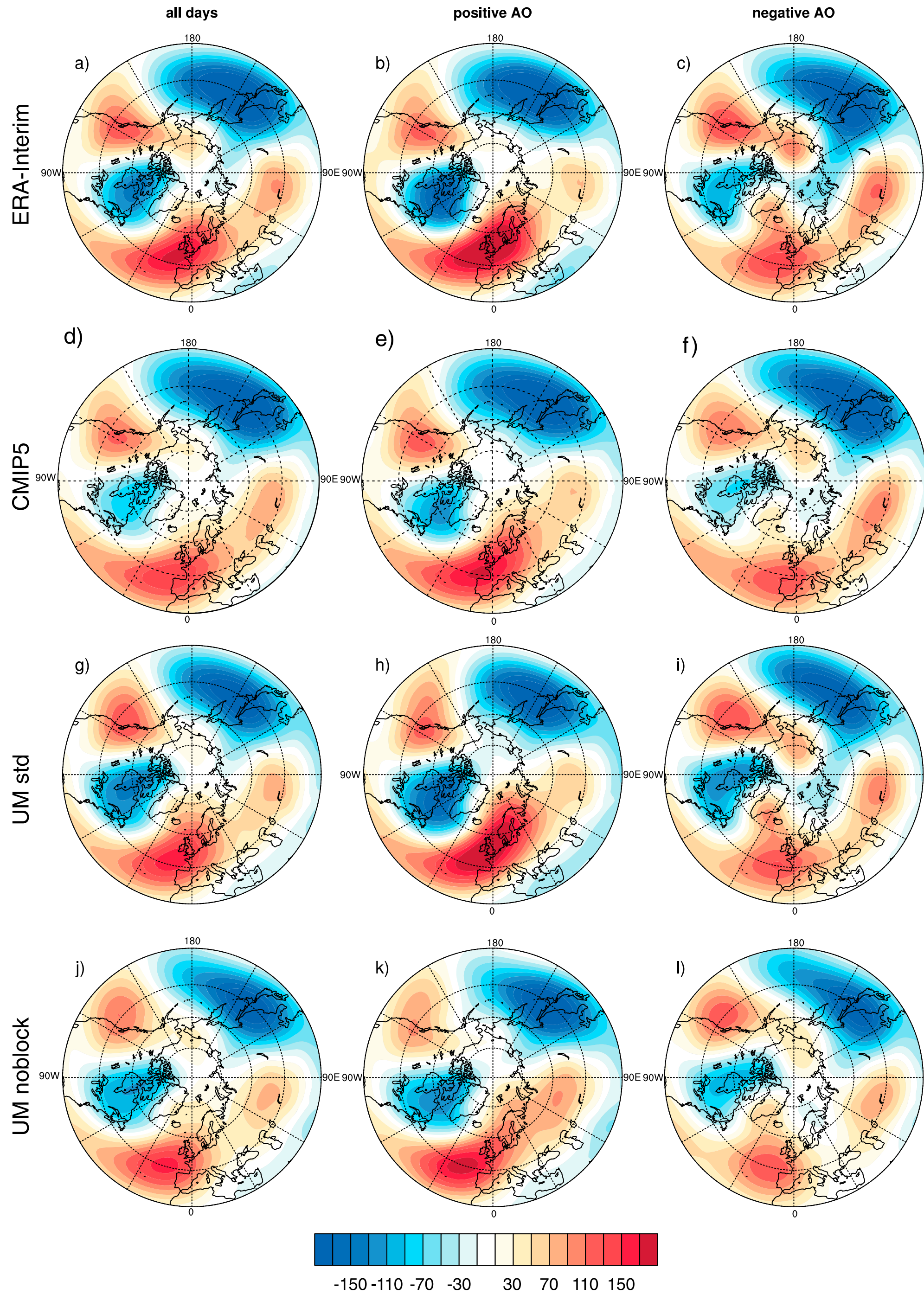


**Figure 1.** Zonally asymmetric component of DJF daily 500 hPa geopotential height (in m) for (a, d, g, and j) all days, (b, e, h, and k) positive, and (c, f, i, and l) negative AO index. ERA-Interim and CMIP5 models are plotted for 1979 to 2005, and UM runs from December 1981 to 2012.

component of the flow represented by the z*500 gradients (see Figure 1) in the positive phase. During the positive AO phase (Figure 2c), too many cyclones in the CMIP5 ensemble travel on a zonal track toward Europe instead of being diverted poleward along the Greenland coast and into the Norwegian Sea. This is consistent with CMIP5 models underestimating the east-west gradient in z*500 or the meridional component of the large-scale flow over the West Atlantic and therefore failing to steer a sufficient number of cyclones poleward. During the negative AO phase (Figure 2d), cyclones in CMIP5 models tend to be too far south over the Atlantic, too many cyclones occur east of the Alps, and too few over the Mediterranean. The latter dipolar

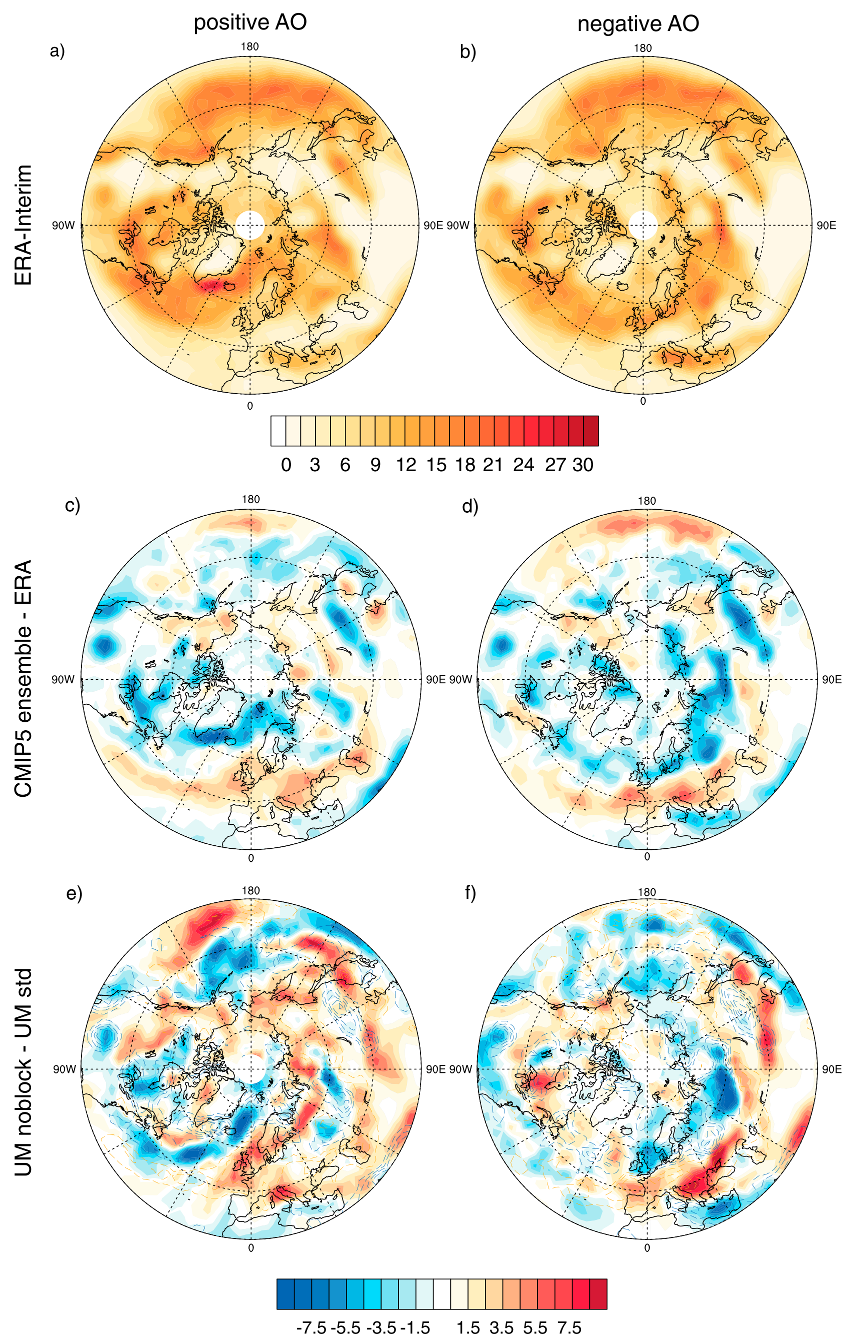


**Figure 2.** DJF track density (ERA-Interim), CMIP5 DJF track density biases, and track density change in UM noblock compared to UM std. Dashed contour lines in the bottom row show CMIP5 ensemble biases (orange for positive and blue for negative biases), with contour spacing of 1.5 and no zero contour. Track density units are number of cyclones per month per unit area, where unit area is equivalent to $10^6$ km$^2$.

bias is also present, albeit much weaker, in the positive phase of the AO. The mean storm track bias of CMIP5 models [*Zappa et al.*, 2013] thus has different contributions from the positive and negative AO phases.

### 3.1.2. Effect of Low-Level Drag

In the UM control experiment, the z*500 patterns are much better represented than in the CMIP5 ensemble. The climatological ridge is somewhat weaker than in ERA-Interim, but its position and orientation agree well with reanalysis data (Figure 1g). In the positive AO phase, the ridge over Europe (Figure 1h) may be slightly too narrow compared to reanalysis. In the CMIP5 ensemble mean, the ridge is clearly placed too far southwest.

In the UM noblock experiment (Figure 1j), the climatological ridge has its maximum farther southwest and a more zonal orientation than in reanalysis. In the positive AO phase (Figure 1k), the ridge shifts as far south and even farther to the west than in the CMIP5 ensemble mean (Figure 1e). In the negative AO composite, the UM control run (Figure 1i) is close to reanalysis, whereas the noblock experiment (Figure 1l) has a very weak northward extension of the East Atlantic ridge, as does the CMIP5 ensemble (Figure 1f).

As for the z*500 pattern, UM storm track biases are considerably weaker and sometimes of opposite sign to the CMIP5 ensemble mean (not shown). Switching off low-level blocking (Figures 2e and 2f) results in changes that map onto the CMIP5 bias pattern over large areas of North America, the North Atlantic, and Eurasia. This includes the negative bias over the Norwegian Sea and positive biases over Great Britain and Italy and the Balkans in the positive AO phase (Figure 2e), as well as a dipole in the eastern Mediterranean in the negative AO phase (Figure 2f). Changes in UM noblock also match areas of both positive and negative track density biases in CMIP5 models over central Asia and North America in both phases of the AO.

The ensemble mean biases in the North Atlantic storm track in CMIP5 models thus match the changes that would occur in the UM in the absence of parameterized low-level drag, consistent with the effect of low-level blocking on the large-scale flow shown by *Lott* [1999]. Such low-level drag is indeed not represented in many climate models or has not been tuned with a focus on minimizing biases in the tropospheric circulation (F. Lott, personal communication, 2015). The effects of low-level drag found in the UM sensitivity experiment do not clearly show up as a difference between models with and without drag (not shown), presumably because there are other differences between the two groups of models. Note that the impact of the stratosphere on Northern Hemisphere wintertime surface circulation is similarly not apparent in differences between subgroups of CMIP5 models [*Manzini et al.*, 2014], even though it is clearly seen in single-model studies [*Scaife et al.*, 2012] and is widely accepted.

Individual models' z*500 fields (not shown) suggest that the CMIP5 ensemble mean bias in the position of the North Atlantic ridge is associated with a stationary wave pattern with a too long total wavelength and waves that follow a too zonal path from their source region in the Rocky Mountains. Since Rossby waves to first approximation propagate along great circles [*Held*, 1983], these biases lead to the ridge over Europe being too far southwest in models (Figure 1d). The wavelength bias is consistent with lacking drag because for a beta-plane channel, the total wave number of stationary Rossby waves $K_s = \frac{\beta}{[u]}$, i.e., excessive zonal winds $u$ lead to smaller stationary wave number and thus longer wavelength. The ratio of the zonal and meridional group velocities, which determines the propagation direction, also depends on the zonal wind [see *Held*, 1983, equation (6.9) and section 6.3.2]. One might thus expect that to first order, excessive zonal winds lead to a more zonal wave propagation, which is consistent with both the CMIP5 ensemble mean biases and the UM noblock experiment. While zonal wind changes between UM noblock and UM std in the Northern Hemispheric upper troposphere are spatially inhomogeneous, zonal winds on the propagation path of planetary waves from the Rocky Mountains toward Europe increase on the order of 3 ms$^{-1}$ in UM noblock, consistent with the above argument that stronger wind should lead to longer wavelengths.

Climate models tend to underestimate the occurrence of European blocking events, in which the climatological westerly flow is reversed for a sustained period of time [e.g., *Anstey et al.*, 2013]. This bias has been related to the overestimation of climatological westerlies [*Scaife et al.*, 2010] and is thus likely to be affected by additional drag. Indeed, the fraction of blocked days over Great Britain and Scandinavia is reduced from 4 % in UM std to 2% in UM noblock (Figure 3) (see *Anstey et al.* [2013] for an analysis of CMIP5 models using the same blocking index). As the fraction of blocked days in ERA-Interim is about 6%, increasing the orographic low-level drag tends to half the amplitude of the model bias in the European blocking frequency. Although the UM std version is still biased in this respect, the improvement due to orographic blocking is highly relevant considering that the bias of the UM noblock experiment is similar to that of the CMIP5 multimodel mean [*Anstey et al.*, 2013]. These results are also consistent with and provide a mechanism for the link between European blocking and storm track biases found across the CMIP5 models by *Zappa et al.* [2014].

### 3.2. Zonal Mean Zonal Winds and Southern Annular Mode Time Scale

In a zonal mean perspective (Figure 4), typical CMIP5 model biases include an equatorward shift of the Southern Hemispheric jet (visible as a dipole bias with too strong winds on the equatorward side and too weak winds on the poleward side of the observed jet location), a similar but less pronounced bias in the

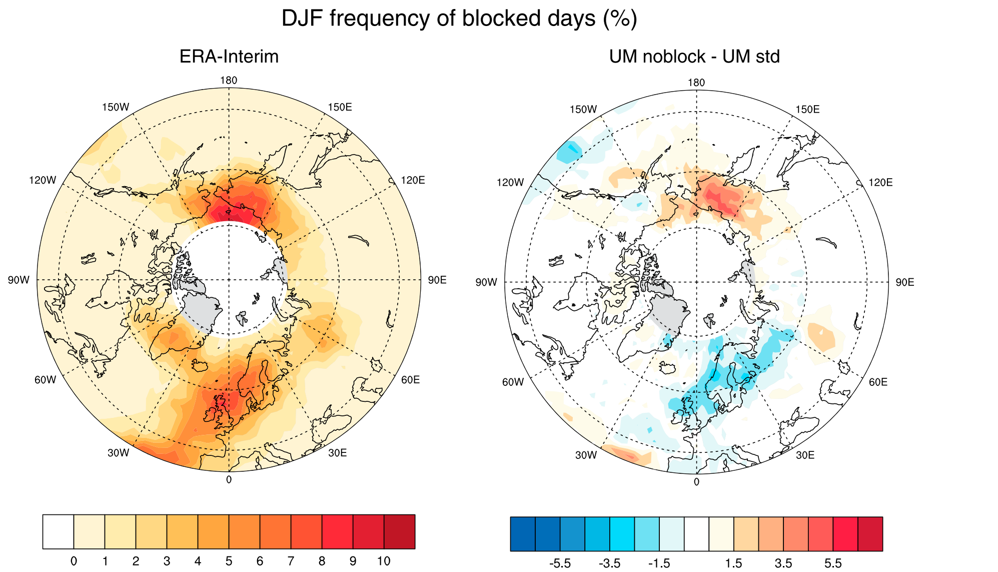


**Figure 3.** DJF 1982–2012 frequency of blocked days for ERA-Interim and frequency changes in UM noblock compared to UM std.

Northern Hemisphere, and an overestimation of tropical easterlies and extratropical westerlies (Figure 4a). The difference between the UM noblock and control experiments projects strongly onto these features (Figure 4b).

It is straightforward that additional low-level drag will help to reduce both excessive easterly and westerly low-level winds in the Northern Hemisphere. For the Southern Hemispheric jet, because of the distribution of land masses and mountains, especially the Andes, the additional drag from the blocking scheme is largely exerted on the jet's equatorward flank (Figures 4c and 4d). As the dominant mode of Southern Hemispheric extratropical variability, the Southern Annular Mode (SAM), corresponds to a north-south displacement of the eddy-driven jet, the parameterized drag is thus a mechanical forcing that projects onto the primary mode of variability. The response to such a forcing is expected to resemble the SAM pattern itself [*Ring and Plumb*, 2007], which is consistent with the response found in the UM experiments.

The time scale of internal variability in a system can be thought of as a measure of the positive and negative feedbacks governing the system, and thereby an indicator of how strongly the system will react to an external forcing (fluctuation-dissipation theorem) [*Ring and Plumb*, 2008]. Climate models tend to overestimate the time scale of annular mode variability compared to observations [*Gerber et al.*, 2008b], which would suggest that they may overestimate the jet response to climate change. The UM std model has an annual mean annular mode time scale of 5.9 days (5.6–6.2) in the Southern Hemisphere, which lengthens to 7.2 days (6.8–7.8) in the UM noblock experiment. In comparison, the annular mode time scale is 6.8 (6.4–7.2) days in ERA-Interim and 10.1 days (9.4–10.8) in CMIP5 models. Time scales uncertainties correspond to 95% confidence intervals obtained from 10,000 bootstrap samples, the CMIP5 range is obtained as the average of individual models' upper and lower bounds.

This suggests that additional low-level drag shortens the time scale of variability, possibly by acting as a negative feedback on jet shifts. Because the annular mode time scale is too short in UM std, this is also consistent with the view that the UM in coarse-resolution setups may have too much parameterized orographic drag [*van Niekerk et al.*, 2016]. For the whole year (Figure 4e), the difference between UM std and UM noblock is small compared to the CMIP5 ensemble mean bias, but in November–January (NDJ) (Figure 4f), when the biases are strongest [*Gerber et al.*, 2008b], the difference between the autocorrelation functions of the UM std and UM noblock experiments is larger than the CMIP5 ensemble mean bias for lags shorter than 20 days. Thus, although missing orographic drag is unlikely to be the only issue in annular mode time scales in climate models, it may account for a substantial part of existing biases.

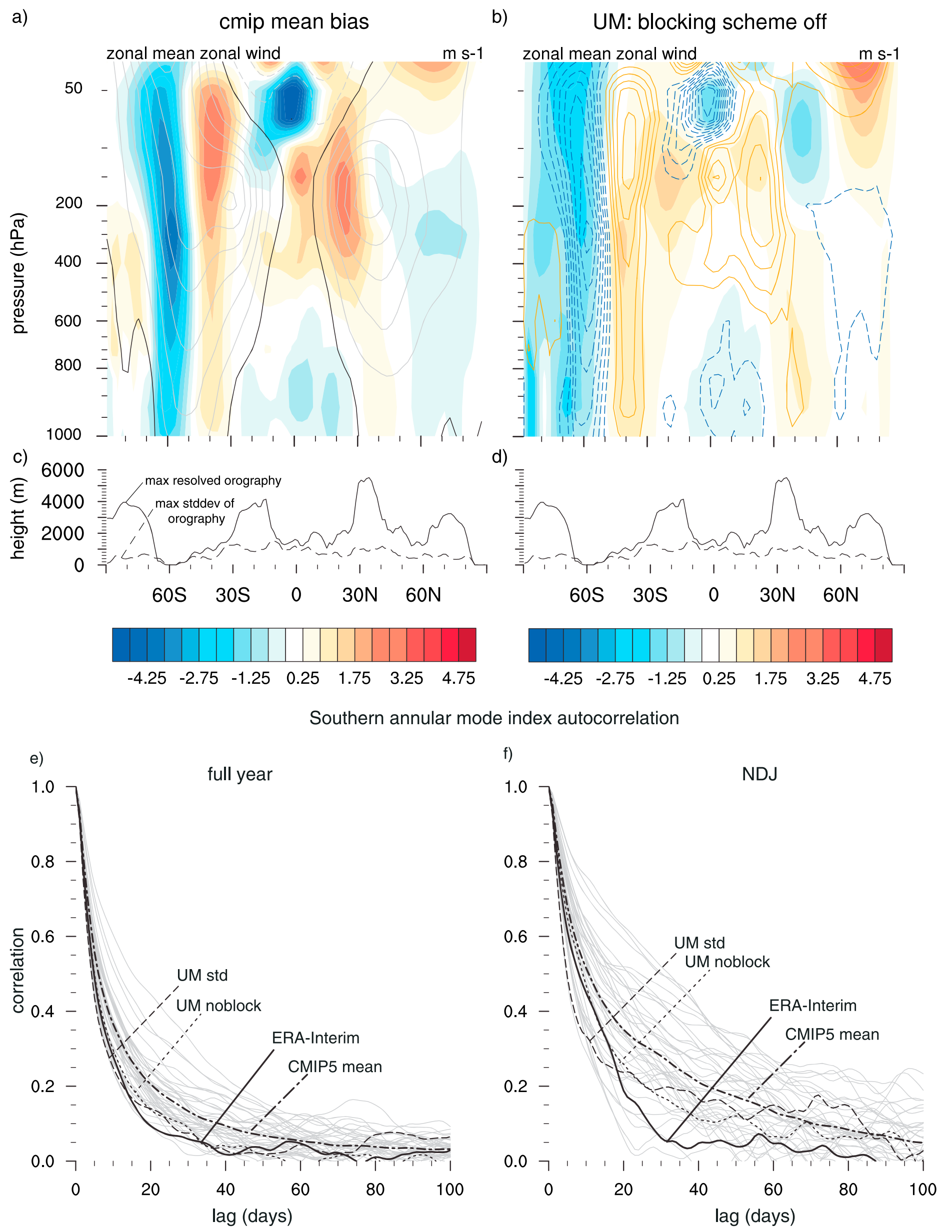


**Figure 4.** Annual mean zonal mean zonal wind: (a) ERA-Interim climatology (gray contours for westerlies, dashed contours for easterlies, and zero wind line in black) and CMIP5 ensemble mean bias (color shading). Contour spacing is 5 ms$^{-1}$. (b) CMIP5 ensemble mean bias (orange contours for westerly and blue for easterly bias) and difference between UM noblock and UM std (color shading). Contour spacing is 0.5 ms$^{-1}$, zero contour omitted. (c and d) The maximum resolved orography (full lines) and standard deviation of orography (dashed lines) at each latitude for the UM at N96 resolution. (e and f) Annular mode index autocorrelation functions for annual and NDJ data. Gray lines show individual CMIP5 models, full black lines ERA-Interim, dash-dotted lines the average of all CMIP5 autocorrelation functions, long dashes the UM std, and short dashes the UM noblock experiment.

## 4. Summary and Conclusions

We have shown that typical climate model biases in wintertime North Atlantic storm track and European blocking, and in Southern Hemispheric jet latitude and Southern Annular Mode time scale, closely resemble the effect of switching off parameterized low-level orographic drag in a model that has a much better representation of the extratropical circulation than the CMIP5 ensemble mean. This suggests that implementing or further tuning low-level blocking schemes in climate models has the potential to substantially reduce long-standing circulation biases and help to improve confidence in future climate projections.

For example, models with an unbiased Southern Hemispheric jet latitude appear to show a smaller poleward wintertime jet shift in a warming climate [*Kidston and Gerber*, 2010; *Bracegirdle et al.*, 2013], although the mechanisms for this are unclear [*Simpson and Polvani*, 2016]. It has been shown before that the improved representation of atmospheric circulation in higher-resolution models is largely due to the better representation of orography rather than improved representation of processes such as Rossby wave breaking [*Berckmans et al.*, 2013; *Jung et al.*, 2012]. The present work emphasizes how substantial improvements in representing the large-scale atmospheric circulation, which is important for extreme events and regional climate, may be accessible without incurring the computational cost of increased horizontal resolution.

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