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Received: 7 October 2024 | Revised: 20 December 2024 | Accepted: 12 February 2025

DOI: 10.1002/asl.1295

RESEARCH ARTICLE

Atmospheric Science Letters RMetS

Sensitivity of European blocking to physical parameters in a large ensemble climate model experiment

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Funding information
Natural Environment Research Council, Grant/Award Numbers: NE/N01815X/1, NE/S004645/1; Met Office Hadley Centre Climate Program funded by BEIS and Defra

Abstract

The occurrence of blocking weather patterns over Europe is analysed in a large ensemble of simulations of a climate model with perturbed physical parameters. The experiments were performed with HadGEM3-GC3 for the UK Climate Change Projections, and comprise a set of 15 coupled simulations supported by a larger suite of 505 atmosphere-only simulations. Despite the systematic perturbation of 47 different physical constants in the atmosphere-only experiments, only three were found to have any impact on European blocking frequencies. These reveal the sensitivity of European blocking to orographic drag in winter and to convective entrainment in summer. However, these sensitivities cannot be traced through to the coupled simulations, due to the smaller and more realistic range of perturbations used and likely also to coupled dynamical effects. Overall, we find that although physical sensitivity to the parameterisations exists, adjustment of the parameters is no replacement for further structural improvement in the representation of these processes in the model.

KEYWORDS

atmospheric blocking, convection, drag, perturbed physics ensemble

1 | INTRODUCTION

Blocking is a persistent mid-latitude weather pattern named for its ability to block the prevailing winds and the normal eastward progression of cyclones. The term encompasses a range of specific flow structures but often features a large and quasi-stationary anticyclone (Woollings et al., 2018). The persistent obstruction of the westerly flow generally leads to settled conditions, which promote anomalously low temperatures in winter but high temperatures in summer, and blocking has been responsible for extreme weather events, from heatwaves and cold snaps to flooding and drought (Kautz et al., 2022).

The simulation of blocking has proved an enduring problem for numerical weather and climate models (Tibaldi & Molteni, 1990), with models typically underestimating the frequency of occurrence of blocked states. Blocking has improved over subsequent model generations, albeit frustratingly slowly. This is due, at least in part, to increased resolution (Davini & D'Andrea, 2020; Schiemann et al., 2020) which improves both the atmospheric dynamics and the orographic forcing (Berckmans et al., 2013). While the low blocking bias appeared

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universal in older model simulations, it is predominantly focused on the Euro-Atlantic sector in more recent models, with less systematic biases over other regions of the northern and southern hemispheres (Davini & D'Andrea, 2020; Patterson et al., 2019; Woollings et al., 2018).

However, several factors besides resolution have been found to affect the model representation of blocking (Woollings et al., 2018), and biases remain even in high-resolution weather prediction systems (Matsueda & Palmer, 2018). One aspect that has received relatively little attention in the literature is the sensitivity of blocking to the physical parameterisations employed in models to represent unresolved processes, with just a few studies highlighting the role of convective and drag parameterisations (Jung et al., 2010; Pithan et al., 2016).

One factor underlying the challenge of simulating blocking is that a wide range of processes is thought to contribute to blocking dynamics (Hauser et al., 2023), with the balance of mechanisms likely altering between regions (Drouard & Woollings, 2018; Nakamura et al., 1997), seasons and from one event to another. A central feature is the interaction of stationary and transient Rossby waves with the background state (Nakamura & Huang, 2018) and each other (Luo et al., 2023; Nakamura et al., 1997; Yamazaki & Itoh, 2013), often leading to large-scale wave breaking (Pelly & Hoskins, 2003). A particular association with rapid cyclogenesis has long been noted (Colucci, 1985), with recent attention focused increasingly on baroclinic processes (Martineau et al., 2022). Diabatic processes are now recognised to contribute to blocking, in particular by enhancing the upward transport of low potential vorticity air along warm conveyor belts in upper-level anticyclones (Methven, 2015; Pfahl et al., 2015; Steinfeld & Pfahl, 2019). The Gulf Stream and Kuroshio oceanic fronts have been shown to play an important role in providing the moisture source and organising the ascent (Mathews et al., 2024; Yamamoto et al., 2021).

The importance of diabatic processes, in particular, motivates a more systematic investigation of the role of physical parameterisations in the simulation of blocking. In this paper, we develop this line of research by investigating the sensitivity of blocking to comprehensive variations of a wide range of physical parameters within a current climate model. The numerical schemes themselves are unchanged; hence, the wider issue of structural uncertainty in modelling is not considered. However, these experiments allow an assessment of the sensitivity of blocking to variations in the strength and behaviour of a wide range of physical parameterisation schemes in a modern climate model. We focus on Europe, where the blocking bias is most systematic.

2 | DATA AND METHODS

Perturbed physics ensembles (PPEs) are a well-developed climate model development and application tool. We use a set of large ensemble PPE experiments performed by the UK Met Office for the latest UK Climate Projections (UKCP18; Lowe et al., 2018). The exploration and selection of parameter combinations for the PPE are described in detail in Sexton et al. (2021) and the regional and global evaluation of the resulting 15-member coupled model ensemble can be found in Yamazaki et al. (2021). The ensemble uses HadGEM3-GC3.05, a version of the Met Office climate model very similar to the one used in the CMIP6 project (Yamazaki et al., 2021). As described by Sexton et al. (2021), a variety of methods were used to determine the range of perturbations applied to a set of 47 key physical parameters from the atmosphere, aerosol and land surface parameterisation schemes to generate a set of model configurations that are plausible yet sample diverse regions of the model's parameter space. Information on each parameter, including their role in the relevant parameterisation scheme and their signature impact, can be found in Sexton et al., table 1. The key steps in the production of the ensemble are depicted in Figure 1 of the same paper. Briefly, lower-resolution atmosphere-only experiments were used to explore this entire parameter space, initially filtering 5-day forecast-style simulations and then 5-year climate runs to inform the development of a set of 25 parameter combinations that were used in the set of coupled experiments. From this initial set of 25 coupled members, only 15 were kept as the parameter combinations from 10 coupled members led to unacceptably poor performance or model failures (Yamazaki et al., 2021). In this work, we used both the atmosphere-only and coupled experiments, which are briefly detailed below.

The 505 atmosphere-only members used to build the set of 25 parameter combinations were run with the model HadGEM3-GA7.05. They cover the 5-year period from September 2004 to December 2009 (the first 3 months are used for spin-off). The prescribed daily sea-ice and sea surface temperatures (SSTs) come from the HadISST2 data set (Titchner & Rayner, 2014). The CO_2 concentrations vary with time and are the same as in CMIP5. The experiments were run on a relatively coarse grid (N96, 1.88° × 1.25°). See Sexton et al. (2021) for more information.

The coupled members were run over the period 1900–2100. From 1900 to 2005 (historical period), the coupled members were forced with historical greenhouse gases, ozone, solar radiation, volcanic forcing and aerosols, as in the CMIP5 protocol. Between 2006 and 2100 (future

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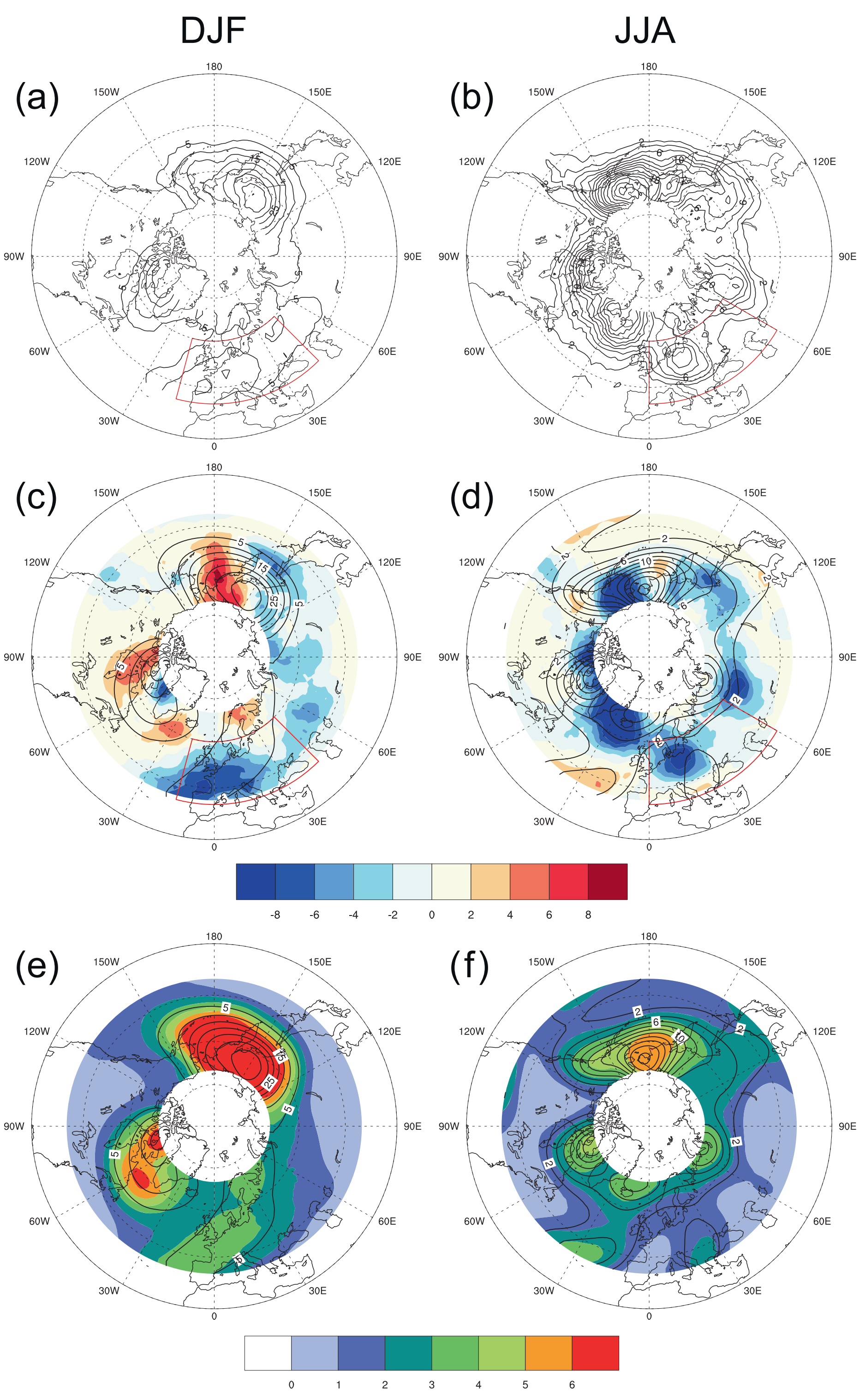

FIGURE 1 (a, b) Climatology of the percentage of days blocked per year in Era-Interim in DJF and JJA, respectively. (c, d) Same for the ensemble mean of the 505-member of the atmosphere-only PPE (contours). Shadings show bias with ERA-Interim. (e, f) Standard deviation (shading) among 505 members. Contours show the ensemble mean of the climatology of the percentage of days blocked per year. Period: 2005–2009.

period), forcing from the RCP8.5 scenario is used as in the CMIP5 protocols (see Yamazaki et al., 2021 for more details). To reduce SST biases in the coupled members, flux adjustments were applied to the surface heat and freshwater fluxes over the entire period (see Yamazaki et al., 2021 for more information on the implementation). Finally, the atmospheric resolution for the coupled members is 0.83° × 0.55° (N216).

Here, we analyse blocking in both the coupled and atmosphere-only simulations using the two-dimensional blocking algorithm of Masato et al. (2013), which searches for persistent and large-scale reversals of the meridional gradient of 500 hPa geopotential height. Comparison is made with the ERA-Interim (Dee et al., 2011) reanalysis on a 0.75° × 0.75° grid, following Drouard and Woollings (2018), Drouard et al. (2021).

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3 | RESULTS

3.1 | Impact of parameter values

The atmosphere-only ensemble tests a large number of parameters over a wide range of parameter space and hence provides most of the information on the sensitivity of blocking to the parameters. Figure 1 presents an overview of the blocking climatology in these experiments in both winter (DJF) and summer (JJA) and a comparison with ERA-Interim (climatologies shown in Figure 1a,b). Despite the short 2005–2009 period, the ensemble climatologies in Figure 1c,d are very similar to those in many climate model studies, with prominent low blocking biases over Europe in winter and Europe / high latitudes in summer consistent with an unrealistic extension of the Atlantic jet into Europe (Davini & D'Andrea, 2020; Woollings et al., 2018). Figure 1e,f show the standard deviation of blocking occurrence across the ensemble, in which the large spread in the European winter blocking bias region is notable. In summer, the mean bias reflects a serious underestimation and a southward shift of the European blocking maxima. The spread between members is weaker in summer than in winter; this is likely in part due to weaker internal variability but also indicates that summer blocking may be less sensitive to the parameter variations.

Figure 2 summarises the parameter sensitivity for blocking occurrence averaged over the large European regions shown by the red boxes in Figure 1. A statistical emulator fitted using a Gaussian process (Lee et al., 2013) is used to estimate the sensitivity to each model parameter. The quantity plotted is the fraction of the total variance of the emulated best fit across the entire parameter space, explained by each parameter (Saltelli et al., 1999). The ‘main effect’ characterises the sensitivity (potentially non-linear) to an individual parameter. Also included is an ‘interaction’ term that quantifies all the effects of interactions between this parameter and others, which are found to be small in these cases. See Rostron et al. (2020) for more details about the emulator.

Despite the large range of parameters varied, winter European blocking in the model is overwhelmingly sensitive to just one parameter: *nsigma*, which scales the amplitude of sub-gridscale orography as used in the orographic gravity wave drag scheme to determine the Froude number. A high value of *nsigma* will result in stronger obstruction of, and drag on, the low-level flow over orography. See Vosper (2015) for more details and physical evaluation (noting that *nsigma* is denoted *n* there). Other parameters in the gravity wave drag scheme are also perturbed, such as *orog_drag_param*, which affects the form drag arising from sub-gridscale orography, yet these are not found to impact the blocking statistics. Summer blocking, in contrast, shows no sensitivity to *nsigma* and only very minor sensitivity to drag processes in general (as indicated by the *gwd_frc* and *gsharp* parameters). Overall, the summer sensitivity is weaker, though there is significant sensitivity to convection parameters, particularly *ent_fac_dp* and *ent_fac_mid*. These control the sensitivity of parameterised convection to deep and mid-level entrainment, respectively, so that higher values of these parameters enhance the damping effect of entrainment on convective activity and depth.

To investigate these relationships further, Figure 3 shows scatterplots of the percentage of days blocked per year, averaged over the red boxes shown in Figure 1a, against the specific parameter values. Considering winter blocking, the sensitivity to *nsigma* is clear, with the higher *nsigma* values corresponding to enhanced drag resulting in increased European blocking (accounting for 29% of the variance across the atmosphere-only runs). This relationship is consistent with the finding of Williams et al. (2020) that *nsigma* is generally the dominant physical parameter to which the extratropical circulation is sensitive in this model, explaining over 50% of the variance in mean MSLP across their ensemble. It is also broadly consistent with the sensitivity of blocking to low-level drag found in the more drastic parameterisation switch-off experiments of Pithan et al. (2016).

The lower panels in Figure 3 confirm the sensitivity of summer blocking to the two entrainment coefficients, though the relationships are weaker than that seen in winter. The sense of the relationships is that increased blocking is related to larger entrainment coefficients, which are known to reduce convection depth and often to suppress active precipitating convection. This sensitivity could be related to the tendency for models to form precipitation too low down within the warm conveyor belts of extratropical cyclones (Hawcroft et al., 2017), with implications for downstream ridge development, but further experiments with more detailed diagnostics would be required to test this. It could also be related to the role of convection in breaking down summer heatwaves and blocks (Zhang & Boos, 2023).

The orange dots in Figure 3 represent the specific parameter values that were adopted in the coupled model experiments. These were chosen from the set of the most realistic atmosphere-only simulations, as assessed for many aspects of global and regional climate representation using a combination of quantitative measures (mean squared error analysis of a range of dynamical and thermodynamic global fields) and qualitative assessment of the emergent regional climatology and circulation in the 5-year simulations (see Sexton et al., 2021 for more

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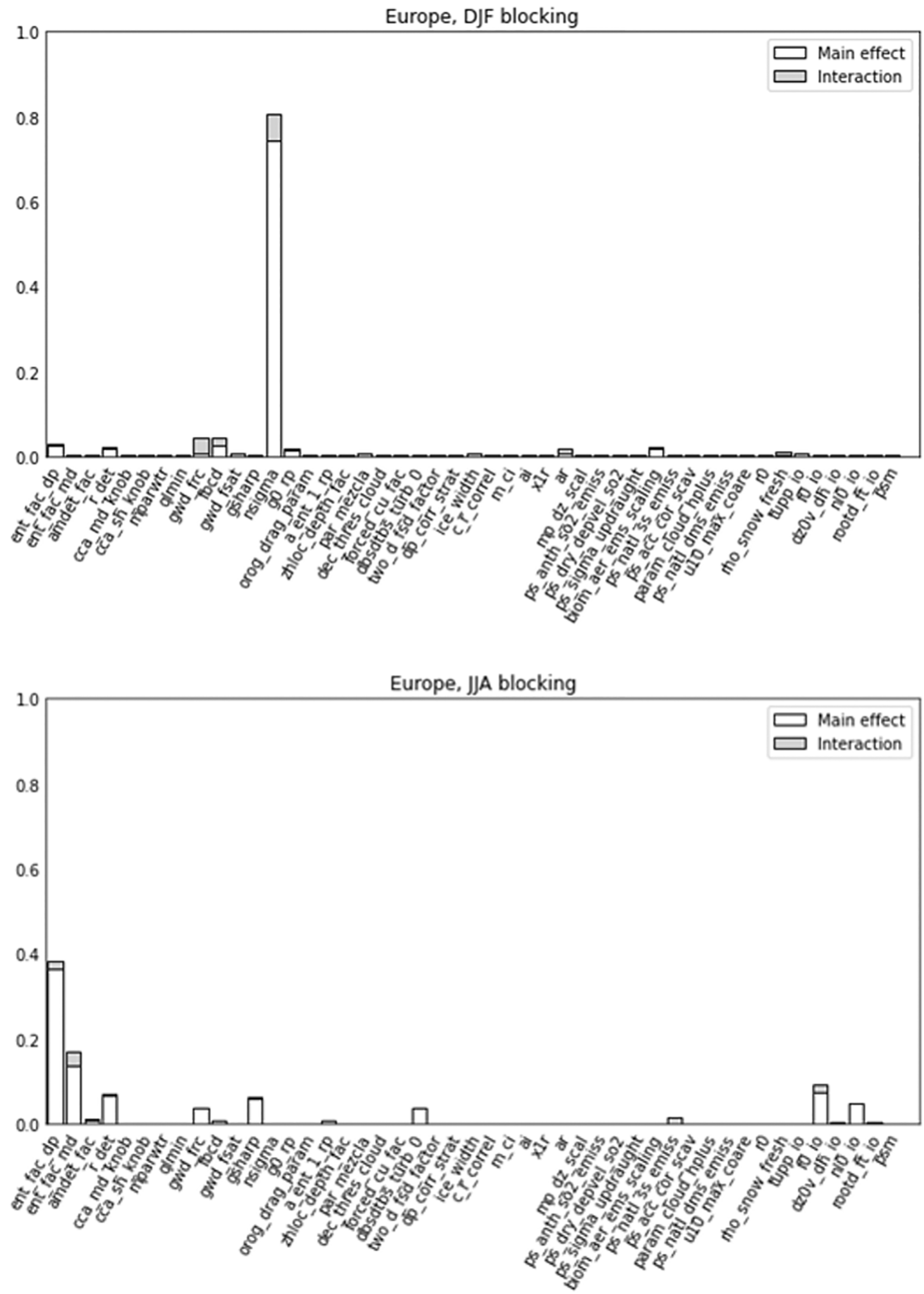

FIGURE 2 Fraction of mean squared error variance in the emulator fit for key parameters and blocking frequency over Europe for DJF (top) and JJA (bottom).

details). Note that blocking frequency itself was not one of the fields assessed. In a subsequent step, the coupled simulations were evaluated, and those that did not have a sufficiently strong Atlantic Meridional Overturning Circulation (AMOC) were discarded. In Figure 3, it is interesting that the blocking sensitivities found in the atmosphere-only simulations are no longer evident over these narrower ranges of parameter values. This suggests that the parameter sensitivities are not expected to be apparent in the coupled simulations, as is indeed found

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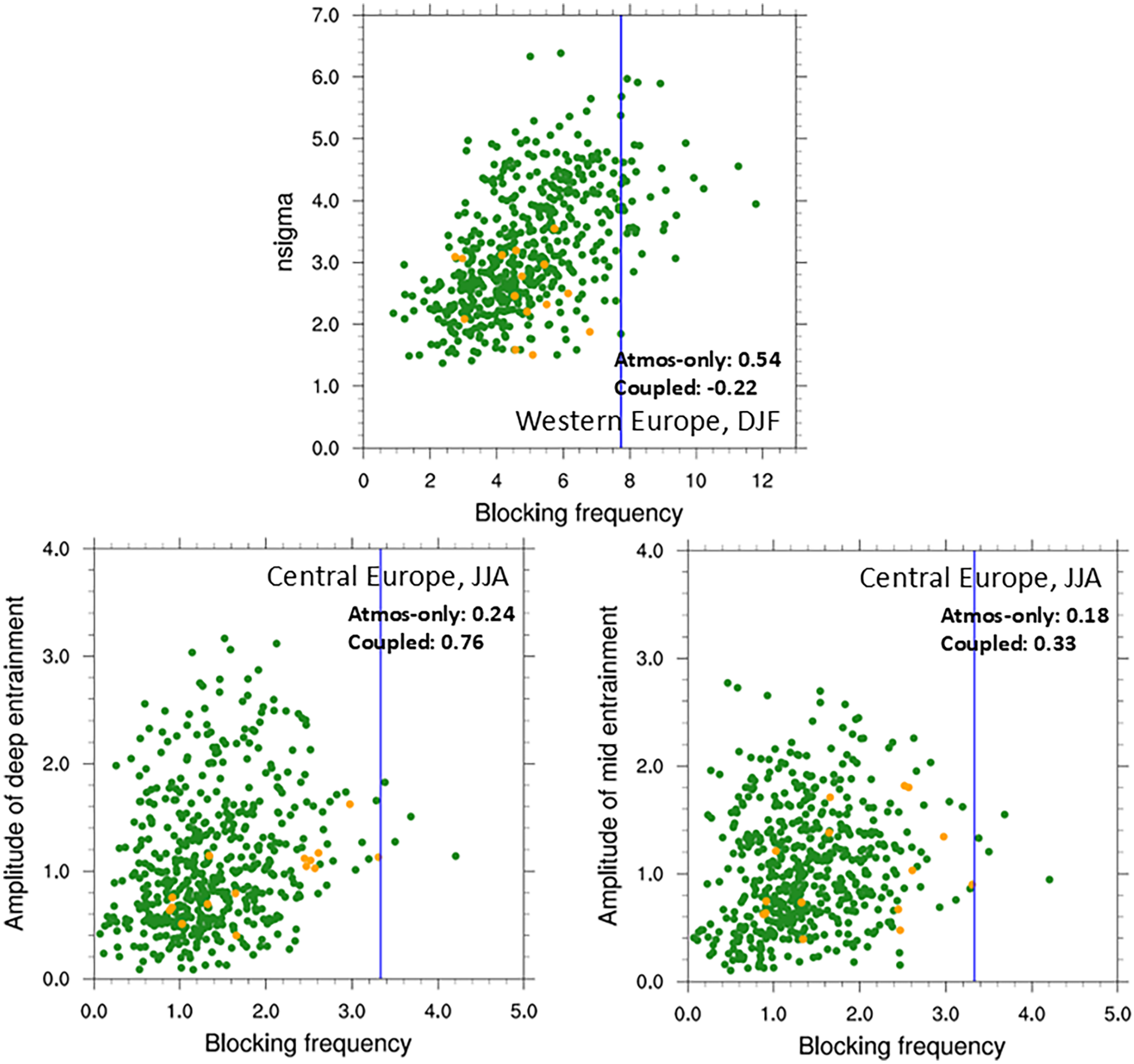

FIGURE 3 (*Top*) Scatter plot of the winter percentage of days blocked per season, spatially averaged over western Europe (red box in Figure 1a) versus *nsigma*. (*Bottom*) Scatter plots of the summer percentage of blocked days per season spatially averaged over central Europe versus the amplitude of the deep entrainment (left) and the amplitude of the mid entrainment (right). Dark green dots represent the 505 members of the atmosphere-only ensemble, orange dots show the 15 members of the coupled ensemble and the blue line shows ERA-Interim. Inset numbers give the Pearson correlation coefficients. This plot is made using data over the period December 2004 – February 2009 (top panel) and June 2005 – August 2009 (bottom panels).

to be the case (see section 3b). Figure 3 also shows the reanalysis blocking frequency, which is generally higher than the model frequencies. In winter, several ensemble members have blocking frequencies comparable to the reanalysis, particularly for high *nsigma* values (3–6). However, these values were not selected for use in the coupled ensemble as giving the most realistic model configurations. Therefore, a too-low *nsigma* in the coupled ensemble could be consistent with the negative bias in blocking frequency observed in winter. In summer, the situation is similar but more dramatic: the blocking bias is worse, and only the most extreme outliers of the atmosphere-only ensemble are consistent with the reanalysis. This suggests that changing the parameter values could decrease the negative blocking bias but would not be sufficient.

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3.2 | Coupled model simulations

We now present a brief analysis of the coupled simulations. These coupled simulations at N216 resolution exhibit relatively low Atlantic SST biases, which have improved the European blocking frequencies compared to earlier models (Scaife et al., 2011). The coupled models show similar blocking frequency bias patterns to the atmosphere-only simulations (Figure S1) though the magnitudes are not directly comparable due to the different simulated periods. Comparing each coupled member with its equivalent atmosphere-only member shows that blocking frequencies are unchanged or slightly increased in the coupled versions (Figure S2), with the increased resolution likely playing a role in this.

Figure 4 summarises the European blocking frequencies in the coupled runs, with the historical period along the x-axis. As expected, the blocking is biased low in both seasons, though in winter in particular the best of the model configurations are within the uncertainty range of the observations. The future period is shown on the y-axis of Figure 4 so that the 1:1 line indicates no change in blocking under forcing. The winter simulations all show a decrease in blocking frequency under climate change, and interestingly, this change is not sensitive to the bias in the present day; blocking reduces by 1–2 days per winter, regardless of whether the initial climatology is 3 or 6 days. This contrasts the CMIP6 relationship found by Davini and D'Andrea (2020), in which models with higher blocking frequencies show a stronger decline under forcing. Hence, a range of models spanning structural uncertainty might be required to identify such relationships. Indeed, a comparison with the CMIP5 models that were used to supplement the PPE in UKCP18 does support this. Figure S3 shows that several CMIP5 models had a more severe DJF blocking bias than in the PPE, and those models with little present-day blocking also show a weak blocking response. In summer, the coupled simulations show no consistent change in blocking; many show a weak future reduction in blocking, in line with previous findings, but several show no significant change. Again, the present-day climatology offers no guide to the future response.

4 | DISCUSSION AND CONCLUSION

Blocking in state-of-the-art climate models such as HadGEM3-GC3 is improved compared to previous model versions, but biases remain, particularly the systematic under-representation of European blocking. This bias is more serious in summer, with fractional biases around 40%, than in winter (25%). Summer blocking is of

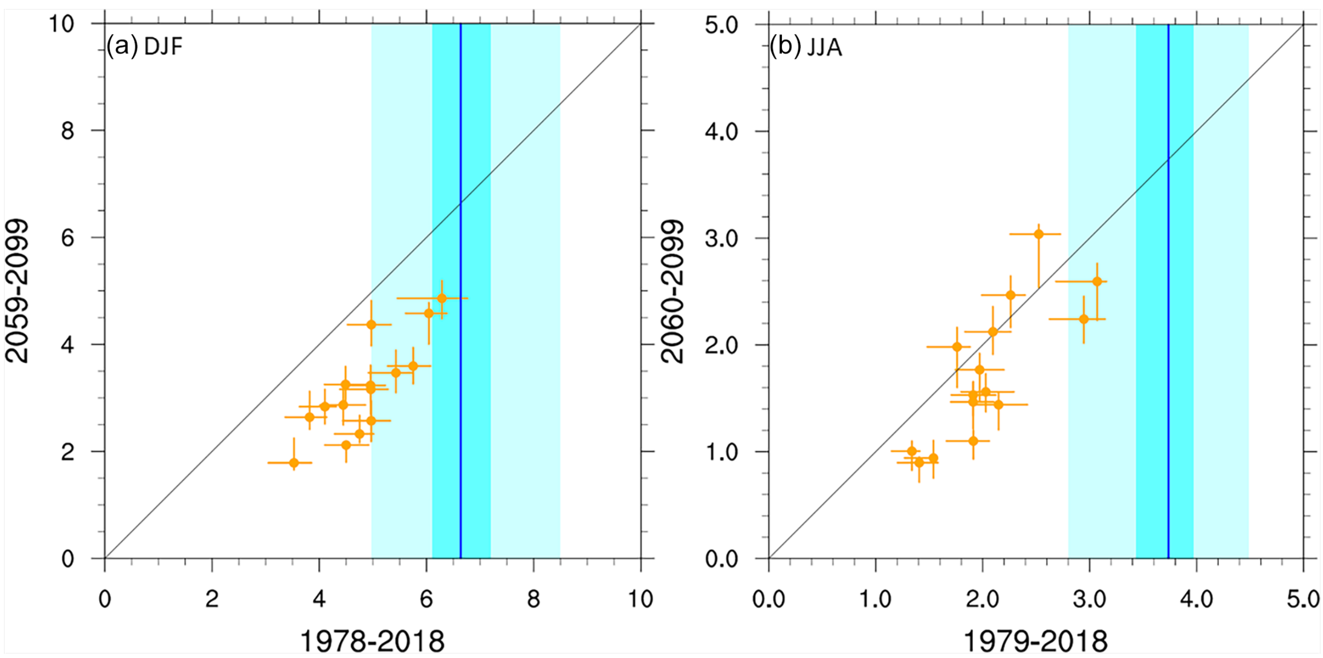

FIGURE 4 The percentage of days blocked averaged over Europe in the coupled members, with the historical period on the x-axis and the future period on the y-axis, for winter (left, see red box on Figure 1a) and summer (right, see red box on Figure 1b). Orange dots show the 15 members of the coupled ensemble, and the orange bars show +/− 1σ confidence interval (based on a bootstrapping method). The blue line shows the percentage of blocked days in ERA-Interim, the solid light cyan shading shows the +/− 1σ range for ERA-Interim and the transparent shading the full confidence interval, both determined from a bootstrap.

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particular importance in a changing climate given the link to heatwaves, so it is noteworthy that this model shows little or no future reduction in European summer blocking.

Our main aim has been to test the sensitivity of European blocking to physical parameters in the model. Overall, very few significant sensitivities were found; out of the 47 parameters varied, only three showed any practically useful relationship to blocking frequencies: one parameter scaling the sub-grid-scale orography (*nsigma*) and two parameters for the convection scheme (*ent_fac_dp* and *ent_fac_mid*). These three, however, suggest real physical links that provide some guidance on how blocking is sensitive to small-scale processes that are not resolved in climate models. The sensitivities show an interesting seasonal dependence, with orographic drag providing a strong constraint during winter but having no effect on blocking in summer. The other two sensitivities highlight a link between parameterised deep convection and summertime European blocking, which may relate to the diabatic pathway for anticyclonic airmass generation within blocks. Interestingly, no such link is seen in winter, and no other sensitivities are found to the array of moist and diabatic physics parameters varied, including in boundary layer, cloud and microphysics schemes.

The identification of these sensitivities has relied on the large ensemble of atmosphere-only simulations used to explore parameter space. Such sensitivities are not apparent in the smaller ensemble of coupled simulations, which could be for several reasons: (i) the smaller range of plausible parameter combinations chosen to generate a realistic and diverse set of model configurations, (ii) the presence of coupled dynamical mechanisms that influence blocking, and (iii) the larger internal variability in coupled simulations that could hinder the detection of an influence. In addition, we note that the *nsigma* drag parameter does have a significant impact on global SSTs in the coupled simulations (Figure S4), which may be a confounding factor.

The blocking sensitivity to physical parameters could be realised through changes in the time-mean planetary scale circulation as well as the dynamics of individual blocking events. Scaife et al. (2010) showed that correcting a model's mean state in post-processing can significantly reduce the apparent blocking bias, and this was supported by Kleiner et al. (2021) using nudging experiments. Often, however, changes in synoptic variability as well as the mean state are needed to improve blocking (e.g. Berckmans et al., 2013). Concerning the parameters identified here, it is possible that a stationary wave response to tropical convection could contribute to the sensitivity to entrainment. However, this is unlikely given the lack of such a signal in northern winter when the tropical stationary wave driving is stronger. Extratropical convection can be an influence on blocking events (e.g. Rodwell et al., 2013) and could also impact the atmospheric mean state through systematic upscale effects, but this would require further investigation.

Regarding the orographic drag, Williams et al. (2020) found that *nsigma* is the model parameter that most strongly influences the mean circulation in the extratropics. Our Figure 3 suggests that increasing *nsigma* could alleviate the winter blocking bias, and Williams et al. show that this also weakens the zonal flow in mid-latitudes, consistent with the expected mean-state influence. However, they also found that the broader Arctic high-pressure bias was exacerbated in response to increased *nsigma* in their experiments, suggesting that this is unlikely to lead to improved simulations for the right reasons. Hence, although the sensitivities we have found provide useful information on physical processes affecting blocking, parameter variation in this model at least is not a replacement for further structural improvement in the representation of physical processes.

AUTHOR CONTRIBUTIONS

Tim Woollings: Conceptualization; funding acquisition; writing – original draft; writing – review and editing; project administration; methodology. **Marie Drouard:** Investigation; methodology; validation; visualization; writing – review and editing; conceptualization; formal analysis. **David M. H. Sexton:** Conceptualization; investigation; writing – review and editing; methodology; validation. **Carol F. McSweeney:** Conceptualization; investigation; methodology; writing – review and editing; validation.

ACKNOWLEDGEMENTS

Tim Woollings and Marie Drouard acknowledge funding from the NERC grants NE/N01815X/1 and NE/S004645/1. David Sexton and Carol McSweeney were supported by the Met Office Hadley Centre Climate Programme funded by BEIS and Defra.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data for the UCKCP-PPE20 experiments are available by arrangement with the Met Office; please use the enquiry form at https://www.metoffice.gov.uk/forms/contact-us-ukcp18.

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REFERENCES

Berckmans, J., Woollings, T., Demory, M.E., Vidale, P.L. & Roberts, M. (2013) Atmospheric blocking in a high resolution climate model: influences of mean state, orography and eddy forcing. *Atmospheric Science Letters*, 14(1), 34–40.

Colucci, S.J. (1985) Explosive cyclogenesis and large-scale circulation changes: implications for atmospheric blocking. *Journal of Atmospheric Sciences*, 42(24), 2701–2717.

Davini, P. & D'Andrea, F. (2020) From CMIP3 to CMIP6: northern hemisphere atmospheric blocking simulation in present and future climate. *Journal of Climate*, 33(23), 10021–10038.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S. et al. (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597.

Drouard, M. & Woollings, T. (2018) Contrasting mechanisms of summer blocking over Western Eurasia. *Geophysical Research Letters*, 45(21), 12040–12048.

Drouard, M., Woollings, T., Sexton, D.M. & McSweeney, C.F. (2021) Dynamical differences between short and long blocks in the northern hemisphere. *Journal of Geophysical Research: Atmospheres*, 126(10), e2020JD034082.

Hauser, S., Teubler, F., Riemer, M., Knippertz, P. & Grams, C.M. (2023) Towards a holistic understanding of blocked regime dynamics through a combination of complementary diagnostic perspectives. *Weather and Climate Dynamics*, 4(2), 399–425.

Hawcroft, M., Dacre, H., Forbes, R., Hodges, K., Shaffrey, L. & Stein, T. (2017) Using satellite and reanalysis data to evaluate the representation of latent heating in extratropical cyclones in a climate model. *Climate Dynamics*, 48, 2255–2278.

Jung, T., Balsamo, G., Bechtold, P., Beljaars, A.C.M., Koehler, M., Miller, M.J. et al. (2010) The ECMWF model climate: recent progress through improved physical parametrizations. *Quarterly Journal of the Royal Meteorological Society*, 136(650), 1145–1160.

Kautz, L.A., Martius, O., Pfahl, S., Pinto, J.G., Ramos, A.M., Sousa, P.M. et al. (2022) Atmospheric blocking and weather extremes over the euro-Atlantic sector–a review. *Weather and Climate Dynamics*, 3(1), 305–336.

Kleiner, N., Chan, P.W., Wang, L., Ma, D. & Kuang, Z. (2021) Effects of climate model mean-state bias on blocking underestimation. *Geophysical Research Letters*, 48(13), e2021GL094129.

Lee, L.A., Pringle, K.J., Reddington, C.L., Mann, G.W., Stier, P., Spracklen, D.V. et al. (2013) The magnitude and causes of uncertainty in global model simulations of cloud condensation nuclei. *Atmospheric Chemistry and Physics*, 13(17), 8879–8914.

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D. et al. (2018) *UKCP18 science overview report*. Exeter, UK: Met Office Hadley Centre, pp. 1–73.

Luo, D., Luo, B. & Zhang, W. (2023) A perspective on the evolution of atmospheric blocking theories: from eddy-mean flow interaction to nonlinear multiscale interaction. *Advances in Atmospheric Sciences*, 40(4), 553–569.

Martineau, P., Nakamura, H., Yamamoto, A. & Kosaka, Y. (2022) Baroclinic blocking. *Geophysical Research Letters*, 49(15), e2022GL097791.

Masato, G., Hoskins, B.J. & Woollings, T. (2013) Winter and summer northern hemisphere blocking in CMIP5 models. *Journal of Climate*, 26(18), 7044–7059.

Mathews, J.P., Czaja, A., Vitart, F. & Roberts, C. (2024) Gulf stream moisture fluxes impact atmospheric blocks throughout the northern hemisphere. *Geophysical Research Letters*, 51(13), e2024GL108826.

Matsueda, M. & Palmer, T.N. (2018) Estimates of flow-dependent predictability of wintertime euro-Atlantic weather regimes in medium-range forecasts. *Quarterly Journal of the Royal Meteorological Society*, 144(713), 1012–1027.

Methven, J. (2015) Potential vorticity in warm conveyor belt outflow. *Quarterly Journal of the Royal Meteorological Society*, 141(689), 1065–1071.

Nakamura, H., Nakamura, M. & Anderson, J.L. (1997) The role of high-and low-frequency dynamics in blocking formation. *Monthly Weather Review*, 125(9), 2074–2093.

Nakamura, N. & Huang, C.S. (2018) Atmospheric blocking as a traffic jam in the jet stream. *Science*, 361(6397), 42–47.

Patterson, M., Bracegirdle, T. & Woollings, T. (2019) Southern hemisphere atmospheric blocking in CMIP5 and future changes in the Australia-New Zealand sector. *Geophysical Research Letters*, 46(15), 9281–9290.

Pelly, J.L. & Hoskins, B.J. (2003) A new perspective on blocking. *Journal of the Atmospheric Sciences*, 60(5), 743–755.

Pfahl, S., Schwierz, C., Croci-Maspoli, M., Grams, C.M. & Wernli, H. (2015) Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geoscience*, 8(8), 610–614.

Pithan, F., Shepherd, T.G., Zappa, G. & Sandu, I. (2016) Climate model biases in jet streams, blocking and storm tracks resulting from missing orographic drag. *Geophysical Research Letters*, 43(13), 7231–7240.

Rodwell, M.J., Magnusson, L., Bauer, P., Bechtold, P., Bonavita, M., Cardinali, C. et al. (2013) Characteristics of occasional poor medium-range weather forecasts for Europe. *Bulletin of the American Meteorological Society*, 94(9), 1393–1405.

Rostron, J.W., Sexton, D.M., McSweeney, C.F., Yamazaki, K., Andrews, T., Furtado, K. et al. (2020) The impact of performance filtering on climate feedbacks in a perturbed parameter ensemble. *Climate Dynamics*, 55(3), 521–551.

Saltelli, A., Tarantola, S. & Chan, K.S. (1999) A quantitative model-independent method for global sensitivity analysis of model output. *Technometrics*, 41(1), 39–56.

Scaife, A.A., Copsey, D., Gordon, C., Harris, C., Hinton, T., Keeley, S. et al. (2011) Improved Atlantic winter blocking in a climate model. *Geophysical Research Letters*, 38(23), 6143–6152. Available from: https://doi.org/10.1029/2011GL049573

Scaife, A.A., Woollings, T., Knight, J., Martin, G. & Hinton, T. (2010) Atmospheric blocking and mean biases in climate models. *Journal of Climate*, 23(23), 6143–6152.

Schiemann, R., Athanasiadis, P., Barriopedro, D., Doblas-Reyes, F., Lohmann, K., Roberts, M.J. et al. (2020) Northern hemisphere blocking simulation in current climate models: evaluating progress from the climate model intercomparison project phase 5 to 6 and sensitivity to resolution. *Weather and Climate Dynamics*, 1(1), 277–292.

Sexton, D.M., McSweeney, C.F., Rostron, J.W., Yamazaki, K., Booth, B.B., Murphy, J.M. et al. (2021) A perturbed parameter ensemble of HadGEM3-GC3.05 coupled model projections: part 1: selecting the parameter combinations. *Climate Dynamics*, 56(11–12), 3395–3436.

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Steinfeld, D. & Pfahl, S. (2019) The role of latent heating in atmospheric blocking dynamics: a global climatology. *Climate Dynamics*, 53(9–10), 6159–6180.

Tibaldi, S. & Molteni, F. (1990) On the operational predictability of blocking. *Tellus A*, 42(3), 343–365.

Titchner, H.A. & Rayner, N.A. (2014) The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations. *Journal of Geophysical Research: Atmospheres*, 119(6), 2864–2889.

Vosper, S.B. (2015) Mountain waves and wakes generated by South Georgia: implications for drag parametrization. *Quarterly Journal of the Royal Meteorological Society*, 141(692), 2813–2827.

Williams, K.D., van Niekerk, A., Best, M.J., Lock, A.P., Brooke, J.K., Carvalho, M.J. et al. (2020) Addressing the causes of large-scale circulation error in the met office unified model. *Quarterly Journal of the Royal Meteorological Society*, 146(731), 2597–2613.

Woollings, T., Barriopedro, D., Methven, J., Son, S.W., Martius, O., Harvey, B. et al. (2018) Blocking and its response to climate change. *Current Climate Change Reports*, 4, 287–300.

Yamamoto, A., Nonaka, M., Martineau, P., Yamazaki, A., Kwon, Y.-O., Nakamura, H. et al. (2021) Oceanic moisture sources contributing to wintertime euro-Atlantic blocking. *Weather and Climate Dynamics*, 2(3), 819–840.

Yamazaki, A. & Itoh, H. (2013) Vortex–vortex interactions for the maintenance of blocking. Part I: the selective absorption mechanism and a case study. *Journal of the Atmospheric Sciences*, 70(3), 725–742.

Yamazaki, K., Sexton, D.M., Rostron, J.W., McSweeney, C.F., Murphy, J.M. & Harris, G.R. (2021) A perturbed parameter ensemble of HadGEM3-GC3. 05 coupled model projections: part 2: global performance and future changes. *Climate Dynamics*, 56(11), 3437–3471.

Zhang, Y. & Boos, W.R. (2023) An upper bound for extreme temperatures over midlatitude land. *Proceedings of the National Academy of Sciences*, 120(12), e2215278120.

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How to cite this article: Woollings, T., Drouard, M., Sexton, D. M. H., & McSweeney, C. F. (2025). Sensitivity of European blocking to physical parameters in a large ensemble climate model experiment. *Atmospheric Science Letters*, *26*(3), e1295. https://doi.org/10.1002/asl.1295

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