Wintertime blocking regimes over Europe are projected to become less persistent in a warming climate

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Key Points:

- The spatial structure of anticyclonic circulations over Europe are projected to stay the same under climate change.
- The persistence of these anticyclonic circulations are in general expected to decrease, although there is considerable inter-model variability
- We show that these qualitative features of the atmospheric response can be reproduced in a simple forced regime model.

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Abstract

In order to better understand the impacts of climate change on Europe, it is important to understand changes in the wintertime large-scale circulation. The framework of weather regimes provides a powerful tool for studying the highly nonlinear Euro-Atlantic circulation, but exactly how these regimes will be altered by anthropogenic climate change is still imperfectly understood. Using the recently developed approach of geopotential-jet regimes, applied to an ensemble of state-of-the-art CMIP6 models, we show that the centres of action of anticyclonic regimes are not projected to change substantially by the end of century, even under an extreme warming scenario. Instead, the regimes are expected to become less persistent, making long-lived blocking events less likely. We show that these two key elements of the regime response can be captured in a simple Lorenz-like model subjected to parameter variations, emphasising the conceptual link between observed atmospheric regimes and the regimes identified in basic mathematical systems.

Plain language summary

The impact of climate change on European weather can be broken into two components: a thermodynamic part relating to increasing air temperature and humidity, and a dynamic part relating to changes in the atmospheric circulation such as the direction and strength of prevailing winds. While the thermodynamic part is relatively well understood, the dynamic part is very uncertain and this is a major problem in constraining European climate projections.

Looking at the winter season, we study the dynamic response of CMIP6 models under climate change using so-called 'regimes', and show that the types of prevailing circulation are not predicted to change strongly. However the regimes are projected to be less long lived.

We also show that these features can be well captured in a simple 5 equation model of regime dynamics, providing a potentially useful tool for understanding regime systems in more detail.

1 Introduction

How will anthropogenic climate change impact Europe? The socio-economic risks associated with extreme weather are likely to intensify over the 21st century (Forzieri et al., 2016), and the large-scale trend is towards warmer conditions with more intense rainfall (Coppola et al., 2021), as a result of reasonably well-understood thermodynamic changes. However, on a regional level, uncertain dynamical changes in the circulation can substantially modify and even reverse this trend. As one example, the CMIP6 ensemble shows a *drying* trend over the Mediterranean (Zappa & Shepherd, 2017), driven by models which predict a strengthening of the polar vortex and tropical amplification under climate change. Uncertainties in the dynamical response of the circulation are thus a major barrier towards developing a more detailed picture of regional climate trends (Shepherd, 2014; Vallis et al., 2015; Shepherd, 2019). The Euro-Atlantic circulation is particularly complex during Boreal winter, due to the highly nonlinear dynamics associated with persistent blocking (Davini & D'Andrea, 2016; Schiemann et al., 2020), latitudinal 'wobbling' of the jet stream (T. Woollings et al., 2010; Parker et al., 2019) and Rossby wave breaking (T. J. Woollings et al., 2008; Masato et al., 2012), all of which are common during the DJF season.

The concept of weather regimes provides a useful framework for understanding this flow by discretising the continuous atmospheric state into a small number of qualitatively distinct flow patterns. Euro-Atlantic regimes are commonly studied either from the perspective of circulation regimes found in the geopotential height field (Michelangeli et al., 1995; Grams et al., 2017; Fabiano et al., 2020) or from a jet regime perspective, based on the trimodal distribution of the low level jet stream (Hannachi et al., 2012; Madonna et al., 2017). Regimes have been used to characterise the flow-dependent predictability (Ferranti et al., 2015) and surface impacts of synoptic weather (Grams et al., 2017; van der Wiel et al., 2019), the impact of remote teleconnections on Europe (Cassou, 2008), and, recently, forced climate trends (Fabiano et al., 2021).

Much of the uncertainty in the wintertime dynamical response to climate change can be framed as uncertainty in the forced response of these regimes. It has been suggested (Palmer, 1993, 1999), using insights drawn from the conceptual Lorenz '63 model (Lorenz, 1963), that the first-order response of regimes to climate forcing will be to change their 'temporal' behaviour – altering the occurrence probabilities of the different regimes – while leaving the 'spatial' characteristics of the regimes – that is, their positions in phase space – largely unaltered. Put another way, climate forcing may manifest as certain historically-present weather patterns becoming more or less probable, but without the emergence of completely new preferred weather patterns. Despite the importance of understanding Euro-Atlantic regime behaviour, this hypothesis has never been tested in climate models. This is at least in part due to the considerable sampling variability in many regime methodologies, and severe deficiencies in regime representation in previous generations of climate models that would make such an analysis unreliable. To avoid such issues, many regime studies assume a set of fixed reference patterns, rendering it impossible to consider the role of spatial regime variability.

Recently, a hybrid approach to regime identification has been introduced (Dorrington & Strommen, 2020; Dorrington et al., 2022), termed geopotential-jet regimes, that integrates both jet speed and geopotential height data. Guided by the observation that the predominantly linear variability of the eddy-driven jet stream is uncorrelated to the non-linear variations of the jet latitude (Parker et al., 2019), variability in 500hPa geopotential height is decomposed into a linearly varying component reflecting meridional gradients induced by jet speed variability, and a nonlinear component that emphasises the multimodal regime dynamics, and jet stream deviations. Geopotential-jet regimes are then identified in this non-linear residual space. As atmospheric blocking events are closely tied to deviations of the jet stream, this approach focuses on anticyclonic regimes rather than cyclonic and zonally symmetric states. Conceptually, This asymmetry is conceptually well-justified, as it is blocking flows which are most strongly associated with highly non-linear dynamics.

In Dorrington et al. (2022), a set of three geopotential-jet regimes were found to be particularly robust to observational sampling variability in a number of reanalyses, and were also well captured by most CMIP6 models in the historical period. Both robustness and a reasonable historical fidelity in models are necessary features for an analysis of a regime's forced dynamics to be trustworthy. Therefore in this work, we are able to test the holistic nature of the Euro-Atlantic regime response, both spatial and temporal, for the first time, building on prior analyses of regimes' temporal response to climate change such as in Fabiano et al. (2021). Specifically, we analyse changes in regime structure in twenty CMIP6 models (detailed in supplementary table 1) under the SSP5-8.5 climate change scenario. This scenario has been characterised as relatively unlikely and represents an extreme future rather than a baseline 'best guess' emissions scenario (Burgess et al., 2020). However as circulation regime occurrence and persistence has been found to vary approximately linearly with increasing warming (Fabiano et al., 2021), we consider only this most extreme scenario here in order to obtain the clearest dynamical signal possible.

2 Methods

2.1 CMIP6 Data

We analyse simulations from the 6th phase of the coupled model inter-comparison project (CMIP6), analysing the twenty model simulations listed in supplementary table 1. We consider both historical experiments, which consist of coupled uninitialised climate runs forced with historical greenhouse gas and aerosol forcings over the 20th century, and future climate projections produced under the SSP5-8.5 climate change scenario.

2.2 Regime methodology and metrics

A single time series of daily DJF Z500 anomalies over the region [80W-40E,30N-90N] was created for each model by appending historical and SSP5-8.5 simulations, and detrended using a cubic fit to the area-averaged Z500 field over the same region. The four leading principal components of detrended Z500 were then computed. A corresponding jet speed time series was also computed, defined as the maximum (oriented Eastward) of 5-day smoothed latitudinally averaged 850 hPa zonal wind speed over the Atlantic domain [100W-80E, 30-90N]. The fraction of principal component variability explicable by linear variations in the jet speed were identified for each model via linear regression, and the space of residuals to this linear best fit was used to identify regimes via K-means clustering. For a more in depth explanation of the method, and expanded motivation, see Dorrington & Strommen (2020) and Dorrington et al. (2022). Jet speed was not detrended, as trends were found to be insignificant, but the linear relationship between principal components and jet speed was calculated separately for the historical and future time periods. After regimes had been identified using K-means, each day in each dataset was assigned to the regime it lay closest to in the residual phase space, unless the pattern correlation of the Z500 anomaly field for that day with the regime Z500 composite (see figure 1) was less than 0.4, in which case it was labelled as a Neutral state.

Regime occurrence is defined as the fraction of days belonging to a given regime, while regime persistence is defined as the probability that a regime event persists from one day to the next, and is found by fitting a Markov chain to the daily sequence of regimes.

2.3 Regime reconstruction

Figures 1d) and e) show area-weighted pattern correlations between Z500 anomaly fields and reconstructed fields computed from the regime time series. Daily reconstructions were obtained by simply using the regime anomaly composite assigned to a given day. Seasonal reconstructions were found by first computing the occurrence fraction of each regime over a given season, and then using an occurrence-weighted sum of the regime anomaly composites as the reconstructed seasonal pattern.

2.4 Molteni Kucharski model

The Molteni Kucharski model is a 5-equation system of ordinary differential equations, which provides a heuristic model of bimodality in the Euro-Atlantic, as driven by the interaction of heat fluxes with climatological standing waves. It therefore provides a natural low-dimensional analogue of the multimodal regimes found in observations and complex models. Its form is given by:

$$\frac{\partial U_{\mathrm{th}}}{\partial t} = \sigma(A - U_{\mathrm{btr}}) + (\gamma - \sigma)A - \kappa U_{\mathrm{th}} - c_a(E^2 - E_0^2)$$
$$\frac{\partial A}{\partial t} = U([B^* - \sigma] - B') - \kappa A$$
$$\frac{\partial B'}{\partial t} = UA - \kappa B'$$
$$\frac{\partial U_{\mathrm{btr}}}{\partial t} = -\kappa_f U_{\mathrm{btr}} + c_f(E^2 - E_0^2)$$
$$\frac{\partial E}{\partial t} = -\tilde{\kappa}_E E + (c_a U_{th} - c_k U_{\mathrm{btr}})E$$

where U_{btr} and U_{th} are barotropic and thermally-driven zonal wind speed anomalies over the Euro-Atlantic respectively, A and B are amplitudes of sinusoidal streamfunction modes over the Euro-Atlantic, in and out of phase with the NAO respectively, E is a basin wide eddy amplitude, and:

$$\tilde{\kappa}_E = \kappa_f \left[\sqrt{1 + \frac{E^2}{E_0^2}} - \sqrt{2}\right] \tag{1}$$
$$U = U_{\mathrm{th}} + U_{\mathrm{btr}} \tag{2}$$

The B^* parameter approximately represents the climatological forcing of the land-sea temperature contrast, and we use changes in this parameter to approximate the impacts of climate change on the system. Other non-varying parameters are described in detail in Molteni & Kucharski (2019). For each parameter value, the model is integrated using a Runge-Kutta fourth-order scheme for 2000,000 model time units. Two regimes were identified based on the sign of the U variable.

3 Results

3.1 CMIP6

Figure 1a) shows the 500 hPa geopotential height (Z500) anomaly associated with each of the three geopotential-jet regimes, averaged across the twenty CMIP6 models for DJF daily data in the historical period 1950-2010. The Atlantic ridge (AR), Negative NAO (NAO-) and Blocking (BLK) patterns are associated with anticyclonic anomalies over the Eastern Atlantic, Greenland and Scandinavia respectively, and capture the main deviations from a zonally symmetric flow seen in the Euro-Atlantic region. Figure 1b) shows equivalent regime anomalies, but now calculated under the future warming scenario SSP5-8.5, for the period 2070-2100. By eye, the end-of-century patterns are almost indistinguishable from those identified in the historical period: it is only by reference to 1c), which shows the difference between b) and a), that changes in the anomalies can be seen. The NAO- regime features a weakened meridional dipole in the SSP5-8.5 simulations, and has its geopotential low shifted further east. The AR regime likewise features a slightly weakened dipole and a very minor eastward shift of the ridge. The BLK regime is largely unchanged but features a slight strengthening of its zonally oriented dipole. These changes, while in places significant at the 5% level according to a bootstrap test, are minor, and are at all gridpoints less than 25% of the amplitude of the circulation anomalies themselves, representing a slight modulation of pattern amplitude but with few changes in the shape of the pattern. We can quantify the importance these small spatial regime changes have on the evolution of the Z500 field, by attempting to reconstruct the Z500 field using the three regime anomalies and assessing the average pattern correlation between the full and reconstructed fields. We do this over the period 2070-2100 using both historical and future regime anomalies. If the nature of the flow is strongly altered in the future climate then the ability of historical regime patterns to characterise future Z500 variability will be reduced. In fact however, on both daily (figure 1d)) and seasonal timescales (1e), there is no substantial difference in the ability of regimes to explain Z500 variability, as assessed via the pattern correlation, when comparing historical and future regime patterns. This strongly supports then the hypothesis of Palmer (1999) that the impact of external forcing on regime patterns is negligible and can be ignored.

Moving on to the temporal variability, figure 2 shows the CMIP6 ensemble mean occurrence and persistence anomalies, with a confidence interval estimated using a drop-1 bootstrap approach. Trends in regime occurrence are quite weak for the AR and BLK regimes, in both cases less than 1% shifts over a 100-year period, and there is no trend in NAO- occurrence. This differs from the findings using classical circulation regimes of Fabiano et al. (2021). There, clear trends in regime occurrence were found, especially for the NAO+ regime. It is likely that methodological differences, namely the inclusion of a neutral state, and a focus on anticyclonic regimes which explains this difference. In our approach regime persistence shows a pronounced signal, with all regimes showing a trend towards reduced regime lifetimes. The signal is strongest for the AR and BLK regimes, which show reductions in the probability of persistence of 2.4% and 2.3% respectively, and a near-linear decrease over time. The NAO- regime also shows a robust decrease in regime persistence, although not as strongly, with a 1.5% decrease in persistence probability over the century, associated with a sharp drop-off after the period 2000-2060. These trends are not large compared to the interannual and even interdecadal regime variability seen in the historical record (Dorrington et al., 2022), but still represent significant shifts, equivalent to the magnitude of historical model bias for some regimes. That persistence trends are most

The ensemble mean trends do however obscure considerable inter-model variability, as shown in figure 3 for persistence (inter-model variability in occurrence is shown in supplementary figure 1). For all regimes, there is no clear model consensus on the sign of climate trends. Models are most confident in the reduced persistence of the AR regime, with 75% of models agreeing. The trend in NAO- regime persistence is particularly uncertain, with the mean response skewed by a small number of models experiencing persistence drops exceeding 10%. It is worth noting that the two most extreme outliers in NAO- persistence are models from the same centre, the Met Office UKESM1-0-LL and HadGEM3-GC31-LL models, and so can not be considered independent of each other. The same effect can be seen to a much lesser degree in the plume of BLK persistence trends, with a few models projecting particularly strong decreases in persistence. The BLK and NAO- persistence trends are linked, as models which project decreased BLK persistence also tend to project decreased NAO- persistence (not shown).

3.2 Molteni-Kucharski model

We have shown that the hypothesis, first inspired by experiments in the Lorenz '63 model, that climate change would leave regime patterns largely unchanged is in agreement with the CMIP6 projections, even under the most extreme climate scenarios. However while Palmer (1999) suggested the climate change signal would project primarily on changes in regime occurrence, here we have found persistence to be most affected.

To address this issue, we look at the Molteni-Kucharski (MK) model (Molteni & Kucharski, 2019) which can be considered as a generalisation of Lorenz '63, coupled to a nonlinear oscillator. It provides a heuristic model of the dynamics of the North Atlantic Oscillation, constructed from a truncation of barotropic dynamics over the Euro-Atlantic

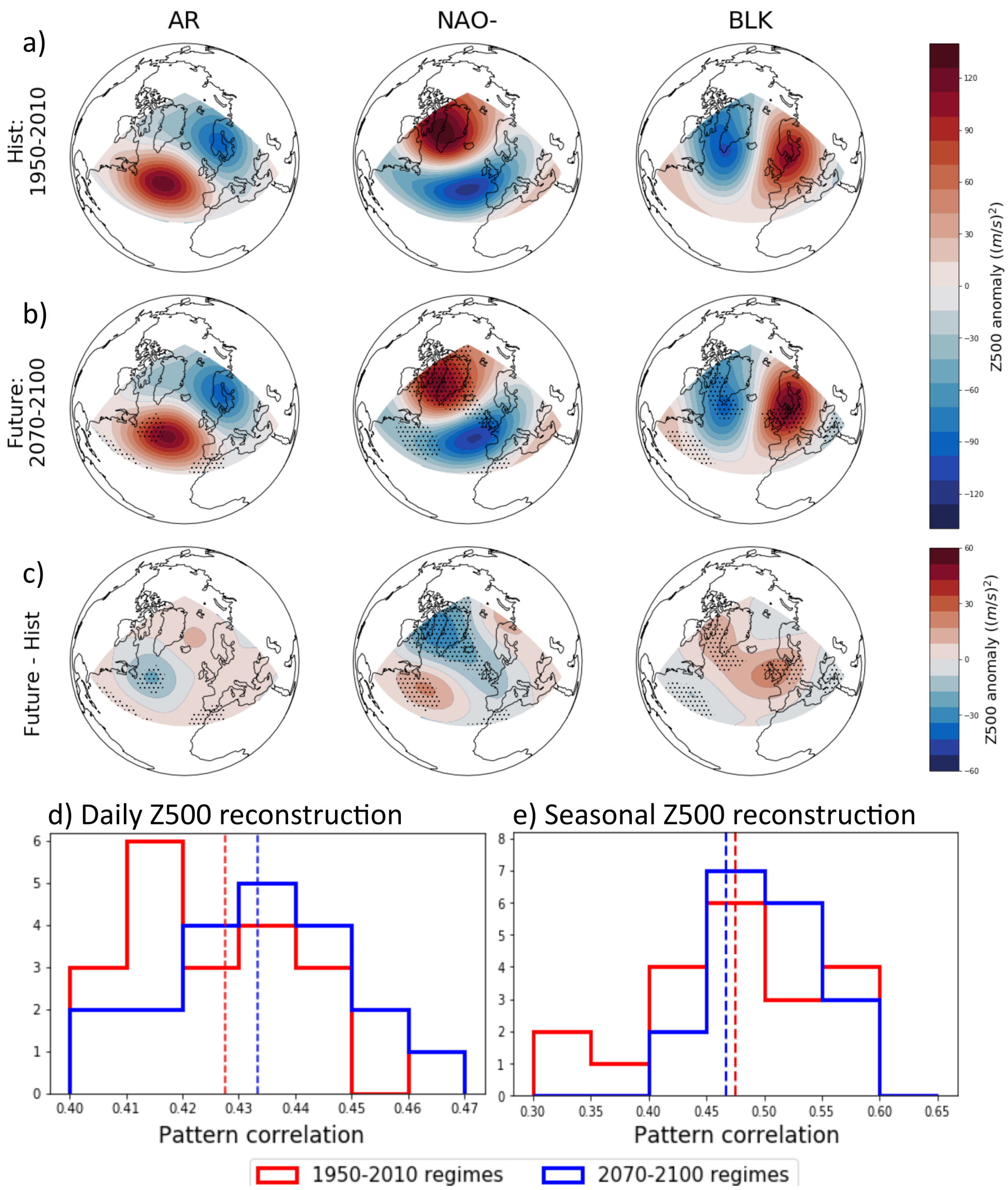

Figure 1: a) Composites of seasonally detrended Z500 anomalies, averaged across all DJF days assigned to a given regime in the period 1950-2010, averaged across the twenty CMIP6 models. b) As a) but for the period 2070-2100, computed using the SSp5-8.5 simulations. Stippling indicates gridpoints where anomalies are different from a) at the 95%level, estimated using a bootstrap approach. c) The difference between b) and a). Stippling as in b). d) A histogram over the twenty CMIP6 models showing the average pattern correlation between the regime assigned to each day in DJF 2070-2100, and the full Z500 anomaly field. Correlations found with historical regime patterns are shown in red, and correlations found with future regime patterns in blue Dashed vertical lines show the ensemble mean value. e) as d), but for correlations of seasonal DJF anomalies, where the regime reconstruction has been computed from a weighted sum of regime patterns, based on their seasonal occurrence probability.

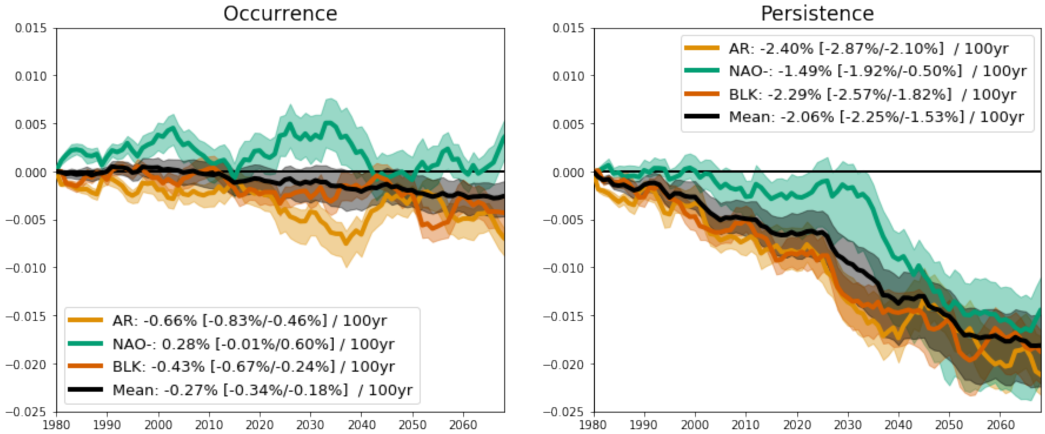

Figure 2: 60-year rolling windows of CMIP6 ensemble mean regime occurrence and persistence anomalies relative to 1950-2010, with the date along the x-axis indicating the central year of the window. Shading indicates a confidence interval in the ensemble mean estimated from a drop-1 bootstrap approach.

region, with a free wave mode interacting with a standing wave generated by climatological ocean heat fluxes and meridional and zonal temperature gradients.

We introduce an analog of climate change into the MK model by altering the B^* parameter, which can be broadly understood as representing changes in the climatological wave mode, consistent with changes in the land-sea contrast anticipated under climate change (Joshi et al., 2008; Dong et al., 2009). However it should be emphasised that the simplicity of the MK model hinders a literal interpretation of individual parameters, and so the model should be understood as a conceptual analog of a forced regime system, rather than representing a direct simplification of the regime dynamics seen in seen in the CMIP6 ensemble.

Figure 4 shows integrations of the MK model subject to variations of B^* across the range $B^* = [11 - 17]$. The system possesses a bimodal regime behaviour, which can be understood as a transition between a zonally symmetric state and a blocked state. As B^* increases, the duration of the regime events decrease. Figure 5a) shows that changes in the mean state of the 5 variables, conditioned on regime, are negligible; just as we see in CMIP6, the impact of forcing does not strongly impact the regime patterns. Regime occurrence (figure 5b)) shows no consistent linear trend across the parameter range, but deviations towards more asymmetrical regime are seen, with occurrence shifts exceeding 5% for $B^* \approx 15 - 16$, a result not clearly in the CMIP6 ensemble.

Trends in regime persistence however are larger, predominately linear and asymmetrical between the regimes, with decreased persistence of 8%-10% between $B^* = 11$ and $B^* = 17$. While of course such a simple model can not capture many of the subtleties seen in the CMIP6 ensemble, the fact that we obtain a qualitative agreement with the CMIP6 forced regime behaviour demonstrates the sometimes surprising efficacy of low-dimensional models for describing complex physical phenomena.

4 Discussion

In this paper we have characterised the forced response of anticyclonic weather regimes – which play a key role in the wintertime Euro-Atlantic cirulation – under climate change within the CMIP6 ensemble. We show for the first time that regime patterns are pro-

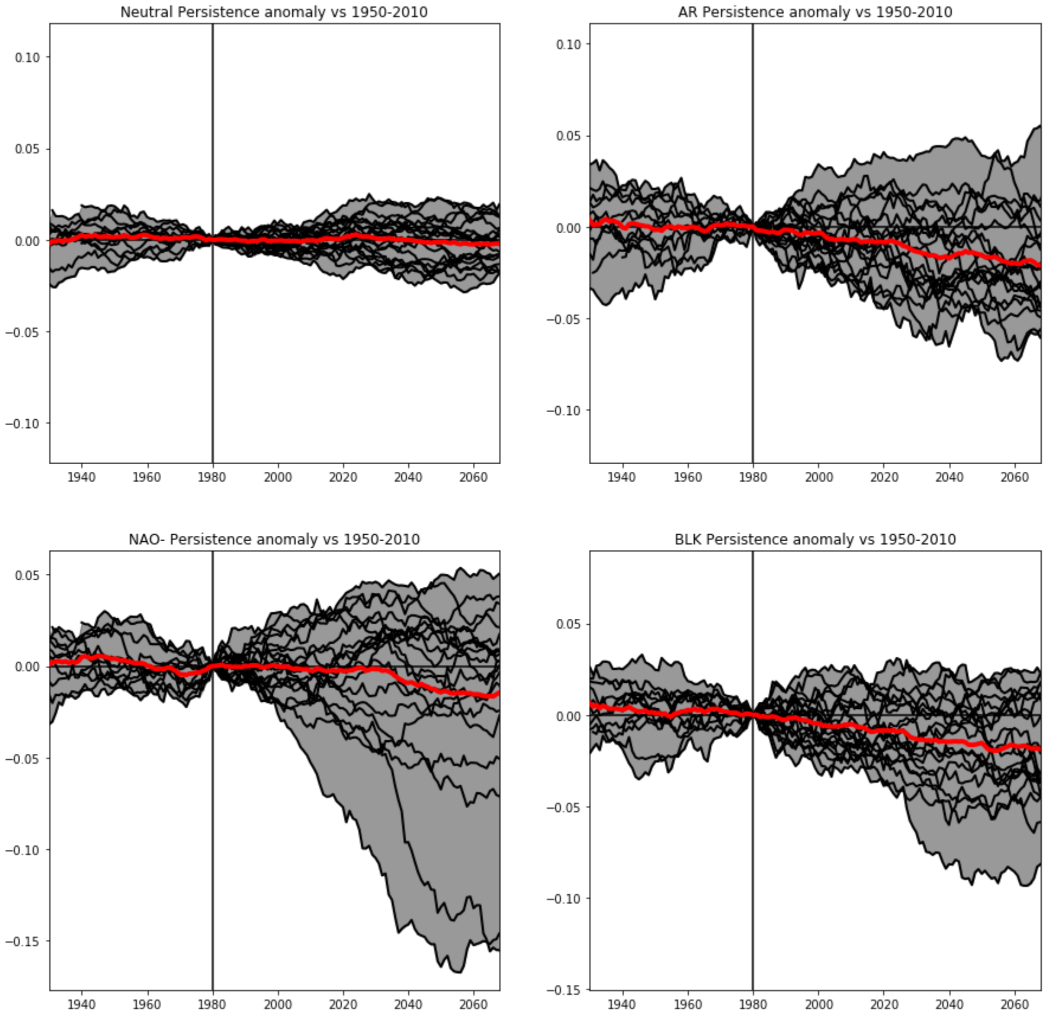

Figure 3: Sixty year rolling windows of regime occurrence anomaly, with each CMIP6 model shown in black, and with the ensemble mean (as in figure 2) in red. The vertical line marks the reference period of 1950-2010. Shading tracks the full range of intermodel spread as a visual guide.

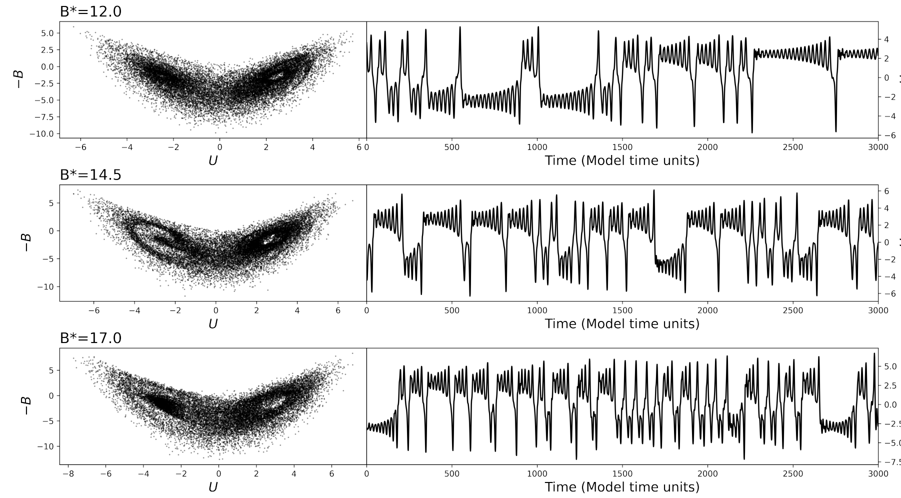

Figure 4: Left: Integrations of the MK model, showing the bimodality of the U-B subspace (equivalent to the x-z subspace in the L63 model), for a range of considered B^* values. Right: Corresponding 3000 MTU time series of the U showing changes in average regime lifetime as B^* increases.

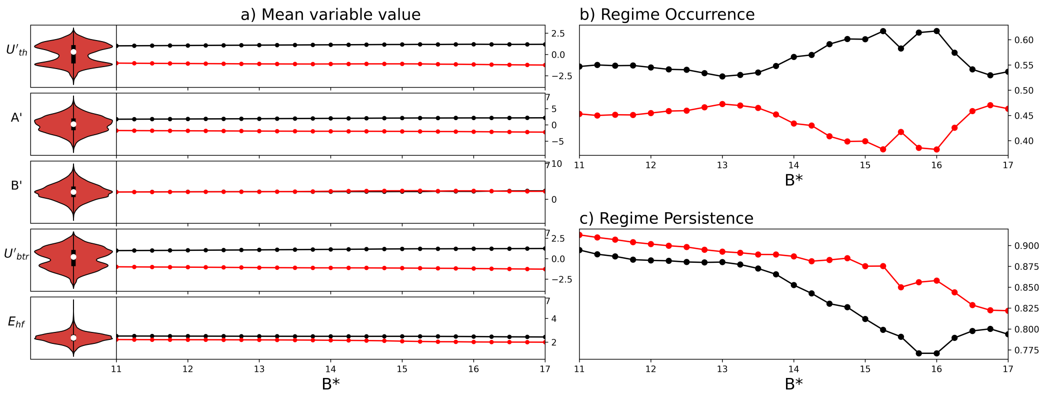

Figure 5: a) Violin plots show probability distributions of the 5 variables in the KM model for the standard parameter value B^*=12. Black and red dotted lines show the average values of each of those variables in the two regimes for increasing values of B^*. b) Changes in regime occurrence as a function of incteasing B^*. c) as in b) but showing regime persistence changes.

jected to remain largely unaltered in a warming climate, suggesting that the position of ridges and persistent blocks in the Euro-Atlantic region is unlikely to alter. As such anticyclonic features are a main driver of wintertime cold extremes and flooding in Europe, this stationarity in patterns places constraints on regional climate changes. We found regime occurrence probabilities largely unaltered in a warming climate, with the dominant impact being a decrease in the persistence of all regimes. Intermodel uncertainty however is large, and there is no model consensus on even the sign of persistence change for the BLK and NAO- regimes.

We showed that the qualitative properties of the CMIP6 regime response – stationary regime patterns with decreasing persistence – can be reproduced in a forced 5-equation conceptual regime model. We therefore answer a long-standing hypothesis on the dynamics of forced regime systems, as well as highlighting the value of simple models for understanding even high-dimensional multi-scale flows. The decrease in regime persistence we document – and the corresponding weak decrease in the total fraction of days featuring anticyclonic blocking regimes – is consistent with previous work finding less intense and less frequent blocking events (Masato et al., 2013, 2014; Rousi et al., 2021; Fabiano et al., 2021). Although there is not a clear consensus on this trend, with some reports of insignificant projected changes in blocking (Bacer et al., 2021), our results lend weight to the majority view of less anticyclonic blocking. This is also consistent with emerging evidence for a more zonal future circulation, and a latitudinal squeezing of the jet (Barnes & Polvani, 2013a; Peings et al., 2017).

This increased zonalisation will tend to result in wetter, more mild winters for Western Europe, with an associated drying trend for north-west Africa and southern Europe, as a result of fewer southern excursions of the low-level jet (Driouech et al., 2010). However, the trends we observe in regime persistence are small compared to interdecadal variability even under the most extreme SSP5:8.5 scenario, as has been seen in other aspects of the Euro-Atlantic circulation (Barnes & Polvani, 2013b; Blackport & Screen, 2020). The implication is that, in the short term and under desirable low-emission scenarios, interdecadal forecasts capturing both forced and internal variability of the Earth system provide the best avenue for understanding 21st century Euro-Atlantic climate. This is especially the case in light of recent results showing decadal forecast skill in both the NAO (Smith et al., 2020) and Euro-Atlantic blocking dynamics (Athanasiadis et al., 2020). One possible risk of decreased regime persistence is an increased number of regime transitions, which are challenging to predict reliably and so could plausibly decrease Euro-Atlantic predictability. However, as NAO- conditions are associated with high predictability on both subseasonal and seasonal timescales (Weisheimer et al., 2017) while the BLK regime is linked to large forecast errors (Faranda et al., 2017; Büeler et al., 2021), it is not possible to comment confidently on likely predictability trends given the large intermodel spread in regime-specific trends.

5 Open Research

Raw CMIP6 data is available from:

`https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/`

Processed regime data is available from:

`https://github.com/joshdorrington/CMIP6_future_regime_changes`

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