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CMIP6 Models Trend Toward Less Persistent European Blocking Regimes 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 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

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The response of the Euro-Atlantic wintertime circulation to climate change is deeply uncertain. The Atlantic jet is caught in a "tug-of-war" between rapid warming trends in both the tropics and the Arctic leading to debate over the changing "waviness" of the jet, which is subject to strong non-linearity and internal variability. From the complementary perspective of weather regimes, there is considerable uncertainty in how atmospheric blocking will alter under climate change. By applying the hybrid approach of geopotential-jet regimes to 6th phase of the coupled model inter-comparison project projections, we show that the centers of action of anticyclonic regimes hardly alter even under severe warming. Instead, regimes are expected to become less persistent, with zonal flow conditions becoming more prevalent, although models disagree on the details of regime changes. Finally, we show the regime response can be captured qualitatively in a simple Lorenz-like model, emphasizing the conceptual link between observed regimes and those 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 twenty-first century (Forzieri et al., 2016), and the large-scale trend is toward warmer conditions with more intense rainfall (Coppola et al., 2021), as a result of reasonably well-understood thermodynamic changes. However, on a regional level, changes in the large-scale circulation can 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. There are large uncertainties in the dynamical circulation response and this is therefore a major barrier toward developing a more detailed picture of regional climate trends (Shepherd, 2014, 2019; Vallis et al., 2015). 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 (Parker et al., 2019; T. Woollings et al., 2010) and Rossby wave breaking (Masato et al., 2012; T. J. Woollings et al., 2008), all common during the winter season.

The concept of weather regimes provides a useful framework for understanding this flow by discretizing 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 (Fabiano et al., 2020; Grams et al., 2017; Michelangeli et al., 1995) or from a jet regime perspective, based on the trimodal distribution of the low level jet latitude (Hannachi et al., 2012; Madonna et al., 2017; T. Woollings et al., 2014). Regimes have been used to characterize 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; Strommen, 2020), 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 was suggested in (Palmer, 1993, 1999), using insights drawn from the conceptual Lorenz '63 model (Lorenz, 1963), that the primary response of regimes to climate forcing will be to change their "temporal" behavior—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 behavior, this hypothesis has never been tested in climate models. This is 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. It was observed in Parker et al. (2019) that the (predominantly linear) variability in the speed of the wintertime Atlantic eddy-driven jet stream is uncorrelated to the (strongly non-linear) variations in the central latitude of the jet. As the Atlantic jet speed features significant interdecadal variability (T. Woollings et al., 2014), Dorrington and Strommen (2020) argued that this linear jet speed variability, which projects onto the 500 hPa geopotential height (Z500) field in the form of a meridional gradient, obscures the nonlinear component of the dynamics, and so makes stable regimes more difficult to identify. They therefore proposed decomposing the principal components of the Z500 field into a linearly varying component explained by jet speed variations, and a nonlinear component that emphasizes the multimodal regime dynamics, and associated jet latitude 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. 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 multiple reanalyses, and were also well captured by most CMIP6 models in the historical period. Both robustness and a reasonable historical fidelity in climate models are necessary features for an analysis of the forced regime response in models to be trustworthy. Now meeting both those criteria, we are able in this work to test the total Euro-Atlantic regime response, including both spatial and temporal variation, for the first time, building on prior analyses of regimes' temporal response to climate change such as in Fabiano et al. (2021).

Specifically, we analyze changes in regime structure in twenty CMIP6 models (detailed in Table S1 in Supporting Information S1) under the SSP5-8.5 climate change scenario. This scenario has been characterized 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. Having separated out jet speed variability within our geopotential-jet regime analysis, we then look at the model behavior in jet speed separately, allowing us to develop a holistic understanding of the large scale circulation changes. Finally, we show that the qualitative features of the CMIP6 forced regime response, which differ somewhat from those hypothesized on the basis of experiments with the Lorenz '63 model in Palmer (1999), can be reproduced in an extended Lorenz-type model developed as a low dimensional analog of the North Atlantic Oscillation by Molteni and Kucharski (2019).

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2. Methods

2.1. CMIP6 Data

We analyze simulations from the 6th phase of the coupled model inter-comparison project (CMIP6), using the twenty model simulations listed in Table S1 in Supporting Information S1. We consider historical experiments, which consist of coupled uninitialized climate runs forced with historical greenhouse gas and aerosol forcings over the twentieth 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 500 hPa geopotential height (Z500) anomalies, restricted to DJF and 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. A cubic fit was required to account for the accelerating increase in geopotential height seen in the SSP5-8.5 simulations. The four leading principal components of detrended Z500 were then computed, as in Dorrington et al. (2022) and Fabiano et al. (2020). 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 [60W–0W, 15–75N]. The fraction of principal component variability explained by linear variations in the jet speed was 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 and 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 data set 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, as introduced and justified in Dorrington et al. (2022), in which case it was labeled as a Neutral state. Including a Neutral state is desirable, as it separates out ambiguous/hybrid flow states which in reality resemble no regime, but which would otherwise be assigned to the regime they were least dissimilar from. Without a neutral state,or employing other approaches such as fuzzy (Smyth et al., 1999) or regularized (Falkena et al., 2020) K-means, such ambiguous states can easily shift from being assigned to one regime to another in response to small changes in the regime patterns or the underlying flow, resulting in potentially misleading changes in regime occurrence.

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 1 day to the next, and is found by fitting a Markov chain to the daily sequence of regimes, in centered 60-year rolling windows; for example, the regime occurrence and persistence centered on the year 2022 for any given model is calculated by fitting a Markov chain to the state sequence covering the period 1992–2052, blending historical and future simulations where necessary. The matrix of transition probabilities is calculated separately for each window, and so we avoid any assumption of stationary temporal dynamics.

Regime reconstructions of daily Z500 fields were obtained by taking the mean composite anomaly of the regime 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.

2.3. Molteni Kucharski Model

The Molteni Kucharski model (Molteni & Kucharski, 2019) is a 5-equation system of ordinary differential equations, which can be considered as a generalization of the archetypal Lorenz ‘63 model, coupled to a non-linear 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 region, with a free wave mode interacting with a standing wave generated by climatological ocean heat fluxes and meridional and zonal temperature gradients.

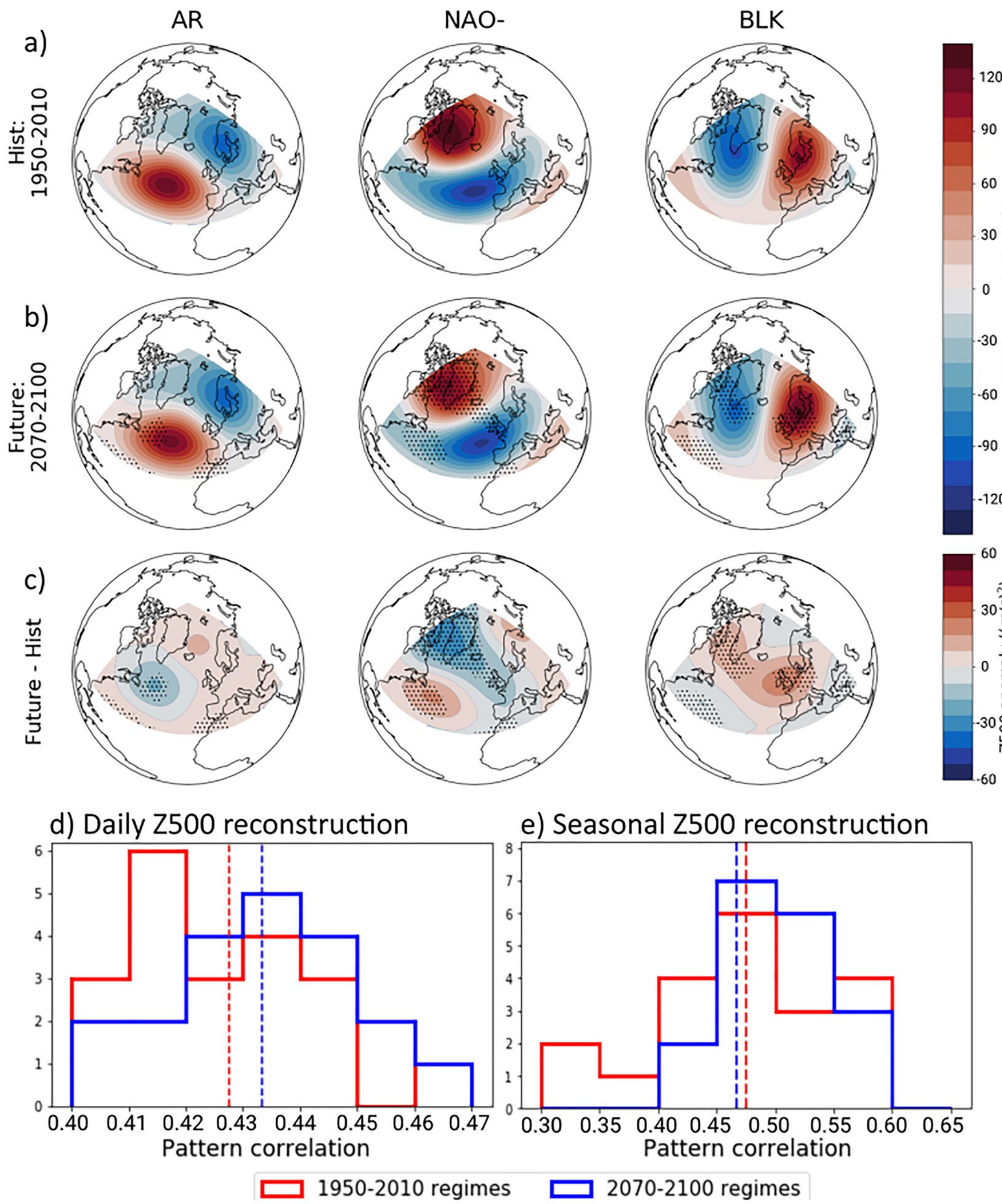

Figure 1. (a) Composites of seasonally detrended Z500 anomalies, averaged across all DJF days assigned to a given regime in the period 1950–2010, averaged across the CMIP6 models. (b) As (a) but for the period 2070–2100, computed using the SSP5-8.5 simulations. Stippling indicates gridpoints where anomalies 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.

It therefore provides a natural low-dimensional analog of the multimodal regimes found in observations and complex models. Its form is given by:

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

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:

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

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 parameters are held constant at $[\gamma = 2, \sigma = 2, \kappa = 0.5, c_a = 1.5, E_0 = 2, \kappa_f = 1, c_k = 1.5]$ and their origin and interpretation described in detail in Molteni and Kucharski (2019). For each parameter value, the model is integrated using a Runge-Kutta fourth-order scheme for 2,000,000 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 Figure 1c, which shows the difference between Figures 1b and 1a, 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.

Figure S1 in Supporting Information S1 shows that there is considerable intermodel spread in these pattern changes, expressing a lack of model consensus particularly in the changing strength of the Atlantic ridge, and in shifts of the NAO- and BLK geopotential height dipoles. Analysis of individual model changes (based on Figure S2 in Supporting Information S1) shows that 17 models feature only minor changes (i.e., pattern correlations exceeding 0.9) between their historical and future regime patterns, indicating that Figure 1c is not merely a result of multiple strong model responses canceling out. The three models that do feature large pattern changes all had low stability in their historical regime structure, suggesting they are among the least reliable contributors to the ensemble, with FGOALS-g3 being a particularly outlying model (cf. Figure S3 in Supporting Information S1). We can quantify the importance of these small changes in regime pattern in a very practical way, by attempting to reconstruct the future Z500 field using the regime composites, 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 characterize future Z500 variability will be reduced. In fact however, on both daily (Figure 1d) and seasonal timescales (Figure 1e), there is no substantial difference in the ability of regimes to explain Z500 variability, as assessed via pattern correlation, when comparing historical and future regime patterns. This strongly supports the hypothesis of Palmer (1999) that the impact of external forcing on regime patterns is negligible and can be primarily ignored.

Moving to the temporal variability of regimes, Figures 2a and 2b shows the CMIP6 ensemble mean occurrence and persistence anomalies respectively, 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. Regime persistence in contrast shows a pronounced signal, with all regimes showing a trend toward shorter regime lifetimes. The signal is strongest for the AR and BLK regimes, which show mean 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 which can produce variations of 5%–10% around the long term average (Dorrington et al., 2022), but still represent significant shifts, equivalent to the magnitude of model bias in the historical period for some regimes.

The ensemble mean trends do however obscure considerable inter-model variability, as shown in Figures 2c–2f for regime persistence (for inter-model occurrence variability see Figure S4 in Supporting Information S1). 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%. Notably, the two most extreme outliers in NAO- persistence are models from the same center, 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. BLK and NAO- persistence trends are linked, with models projecting decreased BLK persistence also tending to project decreased NAO- persistence (not shown).

Having examined both spatial and temporal impacts of climate change on geopotential-jet regime variability, we now must consider forced changes in the jet speed to understand the complete circulation response. From the ensemble mean perspective (Figure 3a) the jet speed shows some increase over the course of the future simulations, although the amplitude is fairly negligible, at only 0.12 m/s by the end of century, and when considering the ensemble variability (Figure 3b) it is clear that there is no robust model consensus on jet speed changes.

In order to further contextualize our results we also consider changes in the occurrence of days with a so-called “central jet”: where the position of the low-level Atlantic jet—as captured by the jet latitude index (Dorrington & Strommen, 2020; Parker et al., 2019)—is between 40° and 52° north. This central peak of the trimodal jet latitude distribution is not associated directly with a single geopotential-jet regime, being characteristic of more neutral, zonally symmetric flow (in ERA5, 50% of central jet days are consigned to the neutral state). We find broad model consensus on increasing central jet occurrence (Figures 3c and 3d), consistent with the decreased occurrence of active blocking regimes, but with much greater model confidence and with a correspondingly greater amplitude. The increased zonalisation of the jet is also consistent with other recent studies (Peings et al., 2017).

3.2. Molteni-Kucharski Model

By applying the approach of geopotential-jet regimes to CMIP6 simulations, We have shown that the hypothesis that climate change would leave regime patterns largely unchanged, first inspired by experiments in the Lorenz ‘63 model, is in agreement with CMIP6 projections even under the most extreme climate scenario. However, while Palmer (1999) suggested the climate change signal would manifest primarily as changes in regime occurrence, here we have found persistence is most affected.

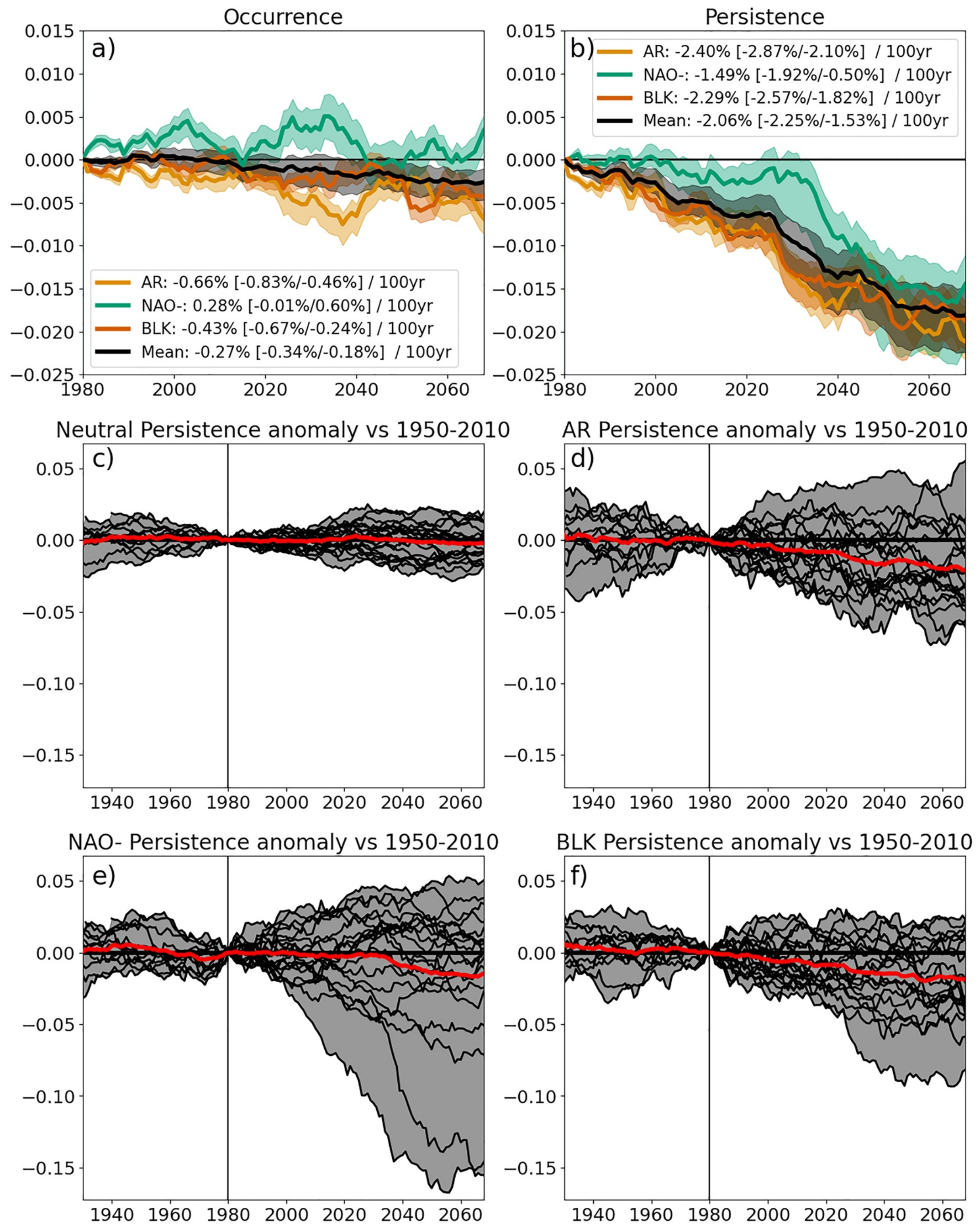

Figure 2. Sixty-year rolling windows of 6th phase of CMIP6 ensemble mean regime occurrence (a) and persistence (b) anomalies relative to 1950–2010, with the date along the x-axis indicating the central year of the window. Shading indicates a confidence interval in the ensemble mean estimated from a drop-1 bootstrap approach. Panels (c–f) show 60 year rolling windows of regime persistence anomaly as in (b), but now showing the intermodel spread for each regime, and with historical variability included for reference. Each CMIP6 model is shown in black, with the ensemble mean, as in (b) included in red as a visual guide. The vertical lines mark the reference period of 1950–2010. Shading tracks the full range of intermodel spread as a visual guide.

We now examine whether these persistence shifts can be obtained in the Lorenz-like Molteni-Kucharski (MK) model, where we introduce an analog of climate change into the model by altering the B^* parameter. This parameter can be broadly understood as representing changes in the climatological background wave, consistent with changes in the land-sea contrast anticipated under climate change (Dong et al., 2009; Joshi et al., 2008). It should

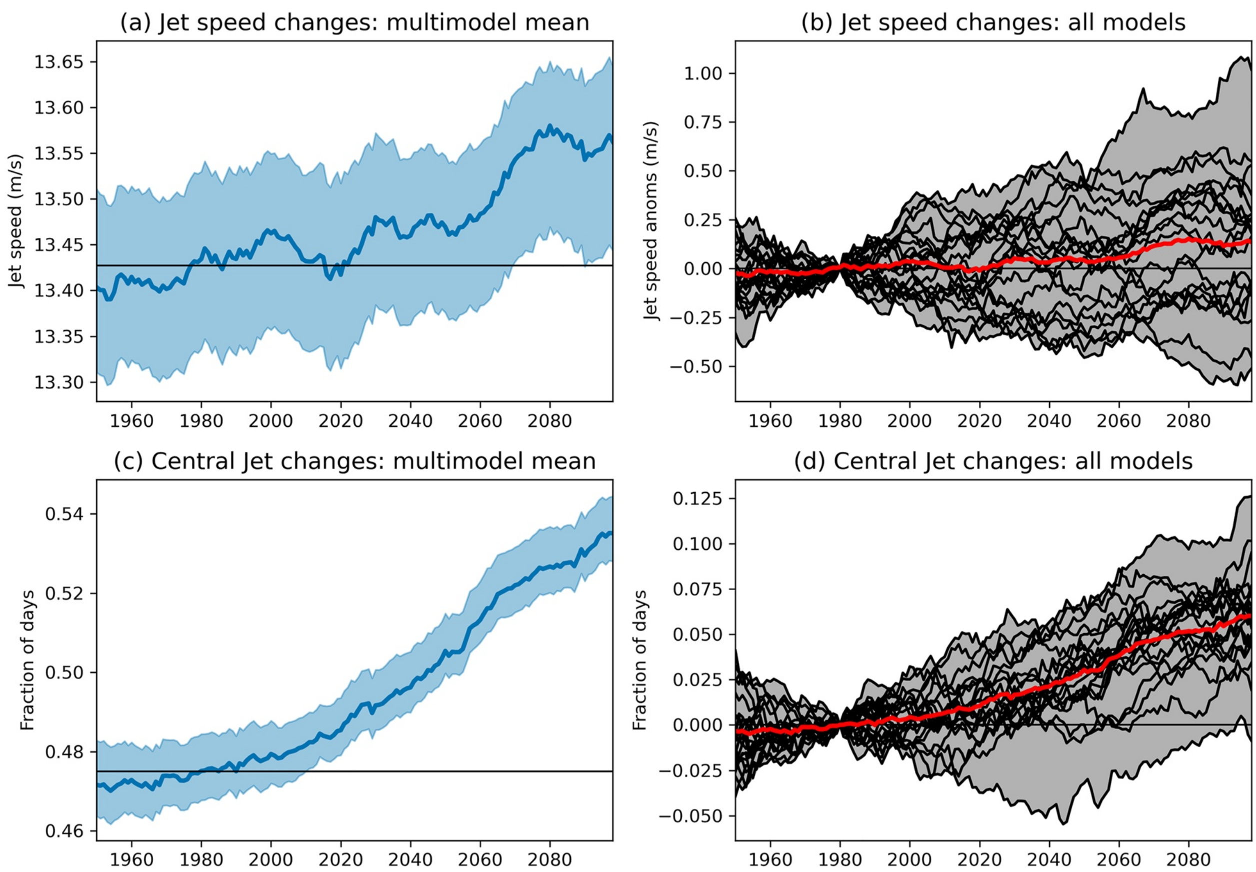

Figure 3. Sixty-year rolling windows of CMIP6 ensemble mean jet speed (a) and anomalies in central jet occurrence (c) relative to 1950–2010. In (a) the mean historical jet speed in CMIP6 is shown by a black line. Shading indicates a confidence interval in the ensemble mean estimated from a drop-1 bootstrap approach. Intermodel variability is shown in panels (b and d), as in Figure 2, in both cases as anomalies to the historical mean of each model.

be emphasized 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 the CMIP6 ensemble.

Figures 4a–4c shows integrations of the MK model for various values of B^*. In all cases the system possesses bimodal regime behavior, 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 visibly decreases. Figure 4d shows that changes in the mean state of the 5 variables conditioned on regime, are negligible over the parameter range $B^* = [11.0, 17.0]$; just as we see in most CMIP6 models, the applied forcing does not strongly impact the regime patterns. Regime occurrence (Figure 4e) shows no consistent linear trend across the parameter range, but deviations toward more asymmetrical regime are seen, with occurrence shifts exceeding 5% for $B^* \approx 15$–16. Trends in regime persistence (Figure 4f) are larger, predominately linear and asymmetrical between the regimes, with decreased persistence of between 8% and 10% as B^* increases from 11 to 17. While such a simple model obviously cannot capture many of the subtleties seen in the CMIP6 ensemble, that we obtain a qualitative agreement with the CMIP6 forced regime behavior demonstrates the sometimes surprising efficacy of low-dimensional models for describing complex physical phenomena.

4. Discussion

In this paper we have characterized the forced response of anticyclonic weather regimes—which play a key role in the wintertime Euro-Atlantic circulation—under climate change using the CMIP6 ensemble. We show for the first time that regime patterns are projected to remain largely unaltered in a warming climate, with only three out of twenty models showing substantial spatial changes. As these models had the worst regime performance in the

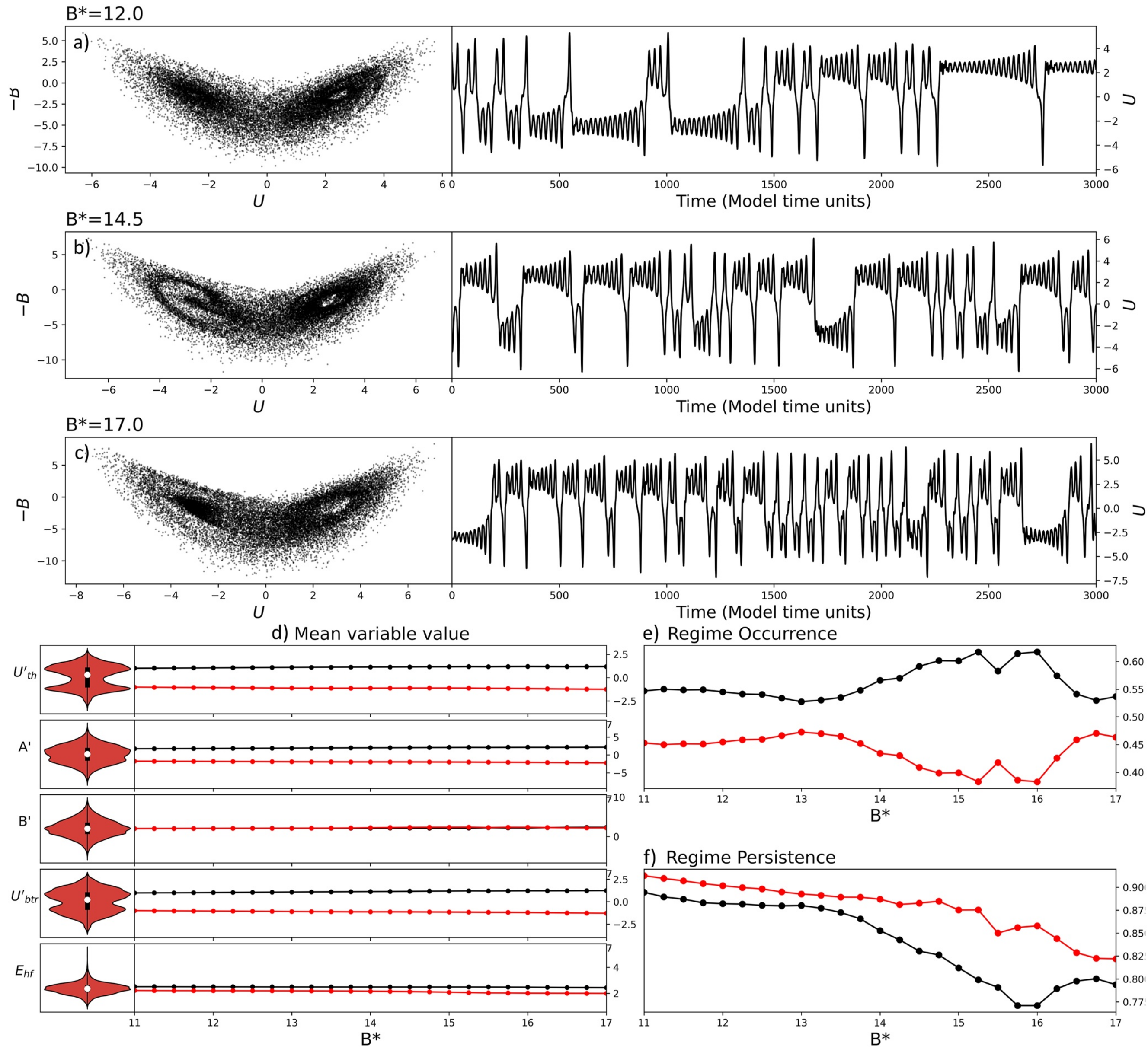

Figure 4. Integrations of the MK model (a–c) Left, showing the bimodality of the *U*-*B* subspace (equivalent to the *x*-*z* subspace in the ‘L63 model), for a range of considered *B** values, and corresponding 3000 MTU time series (a–c) Right, of the *U* showing changes in average regime lifetime as *B** increases. (d) 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**. (e) Changes in regime occurrence as a function of increasing *B**. (f) as in (e) but showing regime persistence changes.

historical period, these outlying changes can likely be attributed to internal model variability rather than a sign of a forced restructuring of Euro-Atlantic regimes. This implies that the positions of ridges and persistent blocks in the Euro-Atlantic region are unlikely to alter, constraining regional climate changes as such anticyclonic features are a main driver of European wintertime cold and precipitation extremes. We found that models are confident in central jet conditions becoming more frequent in a warming climate, consistent with an increased zonalisation of the jet stream, while the occurrence of anticyclonic regimes only weakly decreases. Instead, substantial decreases in the *persistence* of anticyclonic regimes were seen in the ensemble mean, albeit with large intermodel uncertainty even in the sign of persistence changes for the BLK and NAO- regimes. We showed that the qualitative properties of the CMIP6 regime response—nearly stationary regime patterns with decreasing persistence—can be reproduced in a forced 5-equation conceptual regime model. We thereby answer a long-standing hypothesis

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on the dynamics of forced regime systems, and highlight the value of simple models for understanding even high-dimensional multi-scale flows.

Previous work on the impact of climate change on temporal regime variability using classical circulation regimes found strong trends in regime occurrence, especially for the NAO + regime (Fabiano et al., 2021). This is in agreement with our findings for central jet conditions, but is in contrast to the forced response of the geopotential-jet regimes. It is likely that methodological differences, namely the inclusion of a neutral state as discussed in the methods, and our focus on anticyclonic flows explains the bulk of this difference. Decreasing regime persistence, and the corresponding weak decrease in the total fraction of days featuring anticyclonic blocking regimes, is consistent with previous work predicting less intense and less frequent blocking events (Fabiano et al., 2021; Masato et al., 2013, 2014; Rousi et al., 2021). Although there is not a community consensus on this trend, with some reporting insignificant projected changes in blocking (Bacer et al., 2021), our results lend weight to the majority view of less anticyclonic blocking.

Connected to, but not entirely equivalent to, changes in blocking are the changes in the jet stream itself. Especially in the lower troposphere, there is considerable theoretical uncertainty in whether the "waviness" of the jet should increase or decrease as a result of climate change, as the meridional temperature gradient is subject to a "tug of war" between a fast-warming Arctic acting to weaken the gradient and shift the jet south, and a tropical hot-spot acting to reinforce the gradient and shift the jet north (Stendel et al., 2021). We find a clear CMIP6 model consensus for an increasingly central Atlantic jet. This projection of a less wavy, latitudinally squeezed jet, suggests an approximate tie between the two forcings, keeping the jet at fundamentally the same latitude but more closely confined, and is supported by Barnes and Screen (2015) and Peings et al. (2017). While the near-unanimous model agreement on this trend gives confidence, we must also bear in mind evidence that the representation of Arctic-midlatitude links is too weak in models (Cohen et al., 2019; Smith et al., 2022; Strommen et al., 2022), and that this may bias the "tug of war" toward zonal conditions. While Dorrington et al. (2022) showed mid-latitude variability is much improved in CMIP6, it remains unclear whether similar improvements have occurred in these key teleconnections. The decrease in geopotential-jet regime persistence is consistent with this projected zonalisation, but subject to considerable inter-model variability. Given the high confidence in the jet change but the high uncertainty in regime changes, we conjecture that the former drives a model-dependent shift in the latter, but clearly does not constrain it. In other words, the zonalisation of the jet necessarily requires an adjustment in the anticyclonic regime structure, but the exact details of that adjustment may depend either on the model's historical mean state, its representation of synoptic blocking dynamics, or both. Such dependence of the response to forcing on the climatological regime structure has been documented in other contexts (Ruggieri et al., 2021). Teasing out these dynamics in more detail is left to future work.

If the increased zonalisation of the jet does occur, it will tend to result in wetter, more mild winters for Western Europe, and a 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, 2013; Blackport & Screen, 2020). This implies that in the short term and under desirable low-emission scenarios, multidecadal forecasts capturing both forced and internal variability of the Earth system will likely provide the best avenue for understanding 21st century Euro-Atlantic climate. This is especially the case given recent results showing decadal forecast skill in both the North Atlantic Oscillation (Smith et al., 2020) and Euro-Atlantic blocking dynamics (Athanasiadis et al., 2020), although subject to a "signal-to-noise paradox" (Scaife & Smith, 2018), with the models responding too weakly to decadal timescale forcing. One possible explanation for this behavior is biases in models' eddy feedbacks (Hardiman et al., 2022; Scaife et al., 2019; Smith et al., 2022): because eddy feedbacks strongly control regime persistence (Strommen, 2020), it is hard to discount the possibility that the CMIP6 models considered here are severely underestimating the forced decrease in regime persistence.

Data Availability Statement

Raw CMIP6 data is available from: https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/. The CMIP6 models used in this paper are listed in Table S1 in Supporting Information S1. Principal component data and processed regime statistics required to reproduce the results of this study are archived with Zenodo at https://doi.org/10.5281/zenodo.7384049.

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