Check for updates

ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL104696

A Joint Perspective on North American and Euro-Atlantic Weather Regimes

Gabriele Messori[1,2] and Joshua Dorrington[3]

[1]Department of Earth Sciences and Centre of Natural Hazards and Disaster Science (CNDS), Uppsala University, Uppsala, Sweden, [2]Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, [3]Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute of Technology, Karlsruhe, Germany

Gabriele Messori and Joshua Dorrington contributed equally to this work.

Key Points:

- Specific pairs of North American and Euro-Atlantic weather regimes show a close relation
- A joint analysis of the two sets of regimes can provide statistical predictability for anomalies in their occurrence frequencies
- North American regimes have a clear footprint on the European surface weather associated with Euro-Atlantic regimes

Supporting Information:

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

Correspondence to:

G. Messori,
gabriele.messori@geo.uu.se

Citation:

Messori, G., & Dorrington, J. (2023). A joint perspective on North American and Euro-Atlantic weather regimes. *Geophysical Research Letters*, *50*, e2023GL104696. https://doi.org/10.1029/2023GL104696

Received 24 MAY 2023
Accepted 4 OCT 2023

Author Contributions:

Conceptualization: Gabriele Messori, Joshua Dorrington
Formal analysis: Joshua Dorrington
Investigation: Gabriele Messori, Joshua Dorrington
Methodology: Gabriele Messori, Joshua Dorrington
Visualization: Joshua Dorrington
Writing – original draft: Gabriele Messori
Writing – review & editing: Gabriele Messori, Joshua Dorrington

© 2023 The Authors.
This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

Abstract

Weather regimes are recurrent and quasi-stationary large-scale atmospheric circulation patterns, typically linking to surface weather. Two commonly used sets of weather regimes are wintertime North American and Euro-Atlantic regimes. Notwithstanding recent evidence pointing to a connection between winter weather in North America and Europe, there is little knowledge on the possible relation between North American and Euro-Atlantic regimes. Here, we find that specific pairs of North American and Euro-Atlantic regimes show a close visual and statistical correspondence. Moreover, the joint analysis of the two sets of regimes can provide medium-range statistical predictability for anomalies in their occurrence frequencies. Conditioning on North American weather regimes also results in anomalies in both the large-scale circulation during specific Euro-Atlantic regimes, and the associated European surface weather. We conclude that there is a benefit in conducting joint analyses of North American and European weather regimes, as opposed to considering the two in isolation.

Plain Language Summary

Wintertime weather in Europe is closely related to large-scale atmospheric patterns occurring over scales of thousands of kilometers. These patterns, termed weather regimes, are relatively persistent in time, and occur repeatedly. Such weather regimes have been used for many applications, including predicting the weather several weeks in advance. Weather regimes conceptually similar to those identified for Europe have also been determined for North America. In this study, we look at whether and how North American and European weather regimes are related. We show that the two sets of weather regimes have a statistical link, and that accounting for North American regimes can help to gain a more detailed understanding of how European regimes relate to weather in Europe.

1. Introduction

The concept of weather regimes, namely recurrent and quasi-stationary large-scale atmospheric circulation patterns, has a long history in climate science. Early approaches included Grosswetterlagen (Baur et al., 1944) and Lamb weather types (Lamb, 1950), and were chiefly motivated by the observed link between the regimes and surface weather. Weather regimes were then formalized by Charney and DeVore (1979) as corresponding to multiple equilibrium states of the large-scale atmospheric circulation. Since then, the extent to which this view applies to the real atmosphere, and the overall physical grounding of weather regimes, have been debated (cf. Cehelsky & Tung, 1987; Faranda et al., 2016; Fereday, 2017; Hochman et al., 2021). Regardless of their exact physical–mathematical interpretation, a pragmatic application of the regime paradigm has proved a helpful dimensionality reduction tool (Hannachi et al., 2017).

The Euro-Atlantic sector is probably the region that has seen the most extensive application of weather regimes in the climate science literature. A frequent choice is to partition the region's large-scale atmospheric variability into four regimes (Michelangeli et al., 1995; Vautard, 1990), although fewer (Dorrington, Strommen, & Fabiano, 2022) or more (Grams et al., 2017) have been proposed. Moreover, Dorrington and Strommen (2020) argued that the Euro-Atlantic regimes should be considered in conjunction with regimes in the meridional location of the North Atlantic eddy-driven jet (see Woollings et al. (2010)). The four canonical Euro-Atlantic regimes are typically termed Atlantic Ridge (AR), Blocking (Blk), positive North Atlantic Oscillation (NAO) and negative NAO, although there is some variability in this terminology. These regimes have been leveraged for the study of, amongst others, climate dynamics and variability (e.g., Barrier et al., 2013; Madonna et al., 2017), surface weather and extremes (e.g., Domeisen et al., 2020; Yiou & Nogaj, 2004), energy meteorology (e.g., Grams et al., 2017; van der Wiel et al., 2019), climate model evaluation (e.g., Dorrington, Strommen, & Fabiano, 2022; Dorrington, Strommen, Fabiano, & Molteni, 2022; Fabiano et al., 2020), subseasonal to seasonal predictability (e.g., Büeler et al., 2021; Cortesi et al., 2021) and changes in atmospheric dynamics under climate change (e.g., Fabiano et al., 2021; Mallet et al., 2017).

Weather regimes or related circulation regimes have also been defined in other regions of the globe, for example, the Eastern Mediterranean (Alpert et al., 2004; Hochman et al., 2019), East Asia (Yang et al., 2022), Oceania (Kidson, 2000), the Pacific, the full Northern Hemisphere (Lembo et al., 2022), sectors of the Southern Ocean (Messori et al., 2021) and North America. Although the concept of weather regimes was applied to North America at a relatively early stage (Robertson & Ghil, 1999), and North American regimes have regularly appeared in the literature (e.g., Riddle et al., 2013; Vigaud et al., 2018), they have not enjoyed the same widespread application as their Euro-Atlantic counterparts. Nonetheless, North American weather regimes have gained in popularity in recent years (Lee et al., 2019; Messori et al., 2022; Molina et al., 2023; Robertson et al., 2020). Crucially, notwithstanding recent work highlighting the importance of circumhemispheric extratropical teleconnections (e.g., Ali et al., 2021; Davies, 2015), and studies specifically linking concurrent surface weather anomalies in North America and Europe to wintertime large-scale circulation features (Kornhuber & Messori, 2023; Leeding et al., 2023; Messori & Faranda, 2023; Messori et al., 2016; Riboldi et al., 2023), no connection has been made between the North American and Euro-Atlantic regimes. Making such a link presents multiple points of interest, from delineating a simple, categorical picture of teleconnections in a region spanning from the Pacific to Eastern Europe to providing potential statistical predictability pathways for anomalies in the regimes' occurrence frequencies.

Here, we adopt the widely used four-regime classification for both North American and Euro-Atlantic weather regimes, and investigate their relationship. We focus on the boreal winter season, when the weather regimes have seen their widest application. We also link the North American weather regimes to the meridional location of the North Atlantic jet. Finally, we investigate whether conditioning on the North American regimes results in systematic anomalies in the Euro-Atlantic regimes and the associated surface weather in Europe.

2. Data and Methods

The analysis is based on daily ERA5 Reanalysis data from European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020), with a horizontal spatial resolution of 1° between January 1979 and December 2021. We focus our analysis on boreal winter (December, January and February). Anomalies of 2-m temperature (T2m) are computed with respect to a daily climatology, which is smoothed with a 15-days running mean. For daily precipitation we follow the same procedure, but select a longer 90-days running mean to ensure a smooth seasonal cycle.

We define North American weather regimes over 180°–30°W, 20°–80°N and Euro-Atlantic regimes over 80°W–40°E, 30°–90°N. The choice of these regions follows Lee et al. (2019) and Dorrington, Strommen, and Fabiano (2022), respectively. The regimes are computed by performing an empirical orthogonal function decomposition of linearly detrended 500-hPa geopotential height (Z500) anomalies. The Z500 anomalies are computed relative to a daily climatology with a 90-days running mean smoothing. The leading 10 EOFs are retained and a k-means clustering algorithm with $k = 4$ is then applied. We finally assign all days to one of the four regimes based on their minimum Euclidean distance to the cluster centroids. For both the North American and Euro-Atlantic regimes, we additionally define a continuous weather regime index (WRI, Michel & Rivière, 2011). This is a normalized projection of the daily Z500 maps onto the cluster means, thus providing a continuous range of values for each of the 8 weather regimes at all timesteps in our data. The regimes we obtain match closely the previously reported patterns (cf. Figure 1a here with Figure 2 in Vigaud et al. (2018) or Figure 1 in Lee et al. (2019) and Figure 1b here with Figure 1 in van der Wiel et al. (2019) or Figure 1 in Fabiano et al. (2020)). We term, the four North American regimes Arctic High (ArH), Arctic Low (ArL), Alaskan Ridge (AkR) and Pacific Trough (PT), and the four Euro-Atlantic regimes AR, Blk, NAO+ and NAO−. We note that unlike other definitions of the NAO, here the NAO+ and NAO− are not symmetric, and indeed in a weather regime context the NAO− is sometimes also referred to as Greenland Blocking. We do not conduct extensive sensitivity studies on the choice of geographical domains nor on the number of clusters, as we seek to obtain for both domains the canonical weather regimes as used in the previous literature. We nonetheless verify that the qualitative WRI correlations we identify also hold when computing the WRI on non-overlapping domains. We further define three regimes for the

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10.1029/2023GL104696

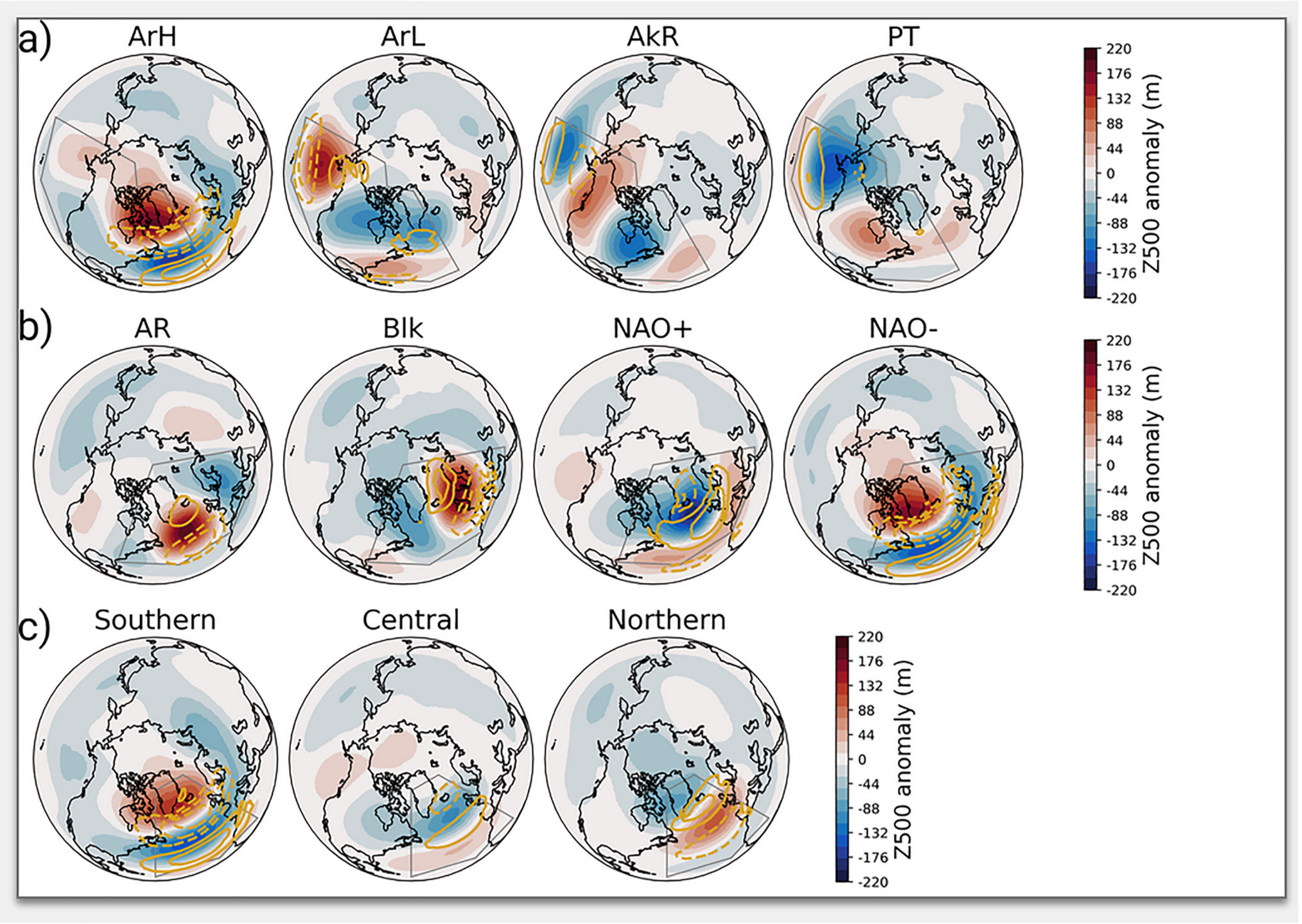

Figure 1. Composite 500 hPa geopotential height anomalies (Z500, m) for: (a) the four North American weather regimes, (b) the four Euro-Atlantic weather regimes and (c) the three jet latitude regimes. Yellow contours show 850 hPa zonal wind (u850) anomalies of ±3, ±6, and ±9 m s^{-1} (negative values dashed). The gray boxes in each plot show the geographical regions over which the regimes are defined. The regime abbreviations are as follows: ArH: Arctic High, ArL: Arctic Low, AkR: Alaskan Ridge, PT: Pacific Trough, AR: Atlantic Ridge, Blk: Blocking, NAO+: positive North Atlantic Oscillation, NAO−: negative North Atlantic Oscillation.

meridional location of the North Atlantic eddy-driven jet stream: a northern, a central and a southern location. We use 850 hPa zonal mean zonal wind (u850) over 60°–0°W, 15°–75°N to define a jet latitude at each timestep, and then follow Parker et al. (2019) in using 39°N and 51°N as cutoff latitudes to separate the three regimes. These locations correspond to local minima in the latitudinal distribution of jet locations.

We determine the Pearson correlations between WRIs for the different regimes and their statistical significance using the scipy.stats.pearsonr function (Virtanen et al., 2020). The statistical significance of occurrence frequency anomalies (Section 3.1) and composite anomalies (Section 3.2) is determined using a bootstrapping procedure with 1,000 samples and applying a false discovery rate correction following Wilks (2016), using the algorithm from Seabold and Perktold (2010).

3. Results

3.1. Relating North American and Euro-Atlantic Weather Regimes

Visually, there is a close correspondence between the ArH and the NAO− (Figures 1a and 1b), which both feature a high-latitude band of positive Z500 anomalies and a band of negative anomalies to the south, with an associated southerly deflection of the jet. ArL and NAO+ share a common dipole anomaly over the North Atlantic with negative values to the North and positive values to the South, but the trough of ArL is shifted toward Greenland and its influence on the Atlantic jet is confined there. The PT and AR regimes both display an anticyclonic feature

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 1
Linear Pearson Correlation Coefficients for the Weather Regime Index Timeseries of the Four North American and the Four Euro-Atlantic Weather Regimes

	ArH	ArL	AkR	PT
AR	0.18*	−0.49*	0.00	0.49*
Blk	−0.26*	0.33*	0.14*	−0.11*
NAO+	−0.70*	0.78*	0.32*	−0.04
NAO−	0.94*	−0.86*	−0.51*	−0.22*

Note. The regime abbreviations are as in Figure 1. Asterisks indicate significant correlations at the 1% level.

in the central North Atlantic. These three pairs of regimes are indeed those that display the strongest positive pattern correlations (Table S1 in Supporting Information S1). To investigate systematically the correspondence between the different regimes, we compute a linear correlation between the North American and Euro-Atlantic WRIs (Table 1). The three above-highlighted pairs of regimes all show very high and significant positive correlations, with the ArH–NAO− being the most highly correlated pair. Correspondingly strong negative correlations are seen when the ArH and ArL or NAO+ and NAO− are swapped for each other. Other regime pairs, such as AkR and NAO− or ArL and AR, also display high absolute correlation values. Notably, all correlations in Table 1, with the exception of AkR with AR and PT with NAO+, are significant. This indicates a strong coupling of the North American and North Atlantic flows. For the two regime pairs that are not significantly correlated, a visual inspection suggests that the Z500 anomalies over the Euro-Atlantic sector are broadly out of phase (Figures 1a and 1b). We repeated the correlation analysis by computing the WRIs on non-overlapping regions, truncating the regime patterns at 45°W (Table S2 in Supporting Information S1). While the magnitude of the correlations decreases, six of the seven regime pairs discussed above remain those displaying the largest absolute correlations. The PT–AR pair is the only one to display a relatively weaker link. Returning to the WRIs computed on the full domains, these same seven pairs of weather regimes display the largest correlations at lag 0, while the correlations between other WRI pairs displaying lower absolute values mostly peak at lags of a few days (Table S3 in Supporting Information S1).

The high WRI correlations point to a possible statistical connection of the weather regimes in the two regions. To complement the correlation analysis, we next calculate anomalies in the frequency of occurrence of Euro-Atlantic regimes conditional on North American regimes (Figure 2a). These largely confirm the picture provided by the correlation values, with for example, ArH events overwhelmingly accompanied by NAO− occurrence, and similarly the ArL and PT being associated with more frequent than usual NAO+ and AR occurrences, respectively. An occurrence anomaly feature that is instead not reflected in the WRI correlations, is the more frequent AR

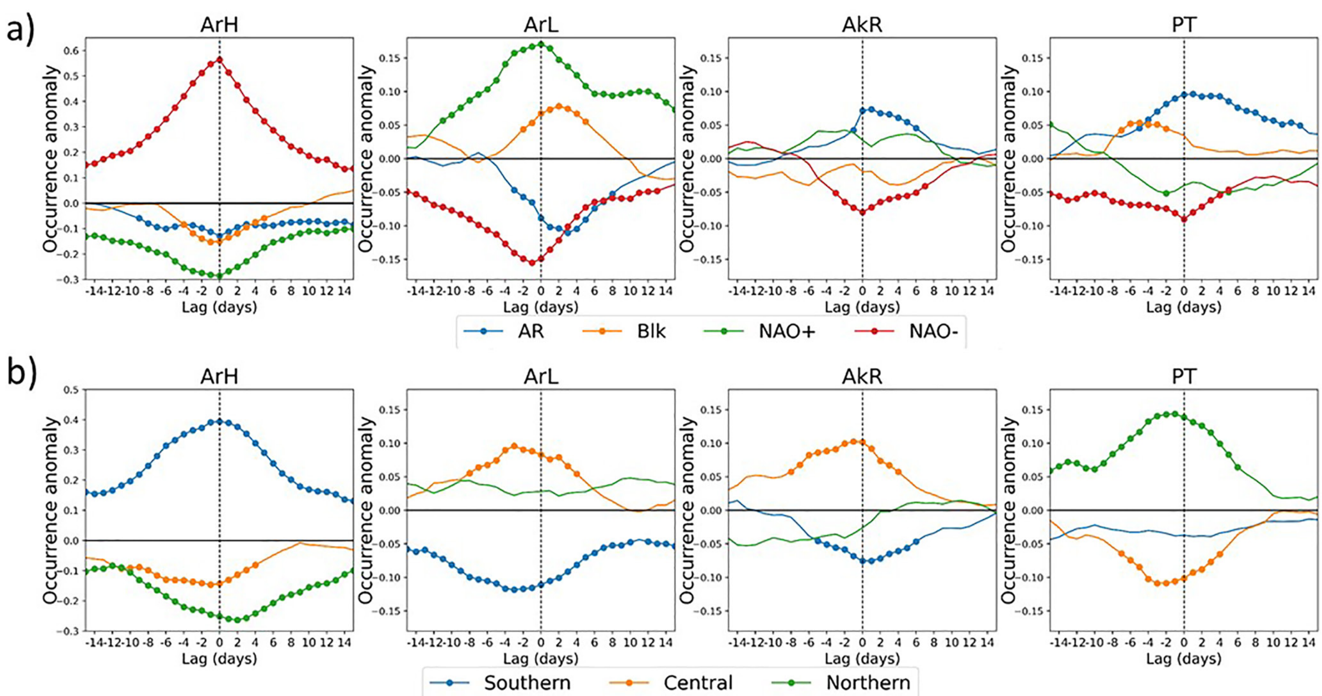

Figure 2. Composite fractional occurrence frequency anomalies of: (a) the Euro-Atlantic and (b) the jet latitude regimes conditioned on the occurrence of a given North American regime at lag 0. The regime abbreviations are as in Figure 1. Dots mark statistically significant anomalies at the 5% level. Note that the y-scale of Arctic High in both (a) and (b) is different to that of the other panels for improved legibility.

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

during AkR. A number of Euro-Atlantic regimes are also heavily suppressed in their occurrence, for example, AR, Blk, and NAO+ during ArH or NAO− and AR during ArL. A striking feature is that significant occurrence anomalies persist for several days prior to and/or following lag 0, namely the day on which the regime occurrence is conditioned. Some Euro-Atlantic regimes present significant occurrence anomalies even at lags of ±15 days: NAO+, NAO−, and AR for ArH, NAO+ and NAO− for ArL and NAO− for PT. A similar analysis can be conducted for the jet latitude regimes (Figure 2b). All four North American regimes correspond to the significantly heightened occurrence of a specific jet regime: southern jet for ArH, central jet for ArL and AkR and northern jet for PT. As for the Euro-Atlantic regimes, also the jet regimes show significant anomalies at large negative and positive lags, for example, the southern and northern jet regimes for ArH, the southern regime for ArL and the Northern regime for PT. In some cases, the jet and Euro-Atlantic regimes provide complementary perspectives on the circulation anomalies conditioned on the North American regimes. For example, a Northern jet is preferentially associated with AR (Madonna et al., 2017), and we find that AR frequency is somewhat enhanced during AkR occurrences. However, AkR itself is associated with an enhanced occurrence of the central jet regime (cf. Figures 2a and 2b).

3.2. Euro-Atlantic Regimes and the Associated Surface Weather in Europe Conditioned on North American Regimes

The close statistical links between the two sets of weather regimes as highlighted in Section 3.1, motivate investigating whether conditioning on the North American regimes may correspond to appreciable anomalies in the large-scale circulation patterns associated with the Euro-Atlantic regimes. To this effect, we compute Z500 anomalies relative to the climatology for the Euro-Atlantic regimes conditioned on each of the four North American regimes, and additionally anomalies relative to the average Z500 field for each Euro-Atlantic regime (Figure 3). All regime pairs confirm that conditioning on the North American regimes results in significant anomalies of the circulation associated with the Euro-Atlantic regimes, although the extent of such anomalies varies. Depending on the North American regime, the AR shows a strengthened or weakened mid-Atlantic ridge and a modulation of the trough over Scandinavia which, in the case of the ArL, almost vanishes (Figure 3a). Blk shows a significantly strengthened anticyclone over Scandinavia when occurring in conjunction with PT (Figure 3b), while the NAO+ in conjunction with ArH shows a tripole wave-like anomaly pattern in the North Atlantic rather than the more canonical meridional dipole (Figure 3c). Finally, the NAO− shows a clear zonal shift between the cases when it co-occurs with ArH and those when it co-occurs with ArL (Figure 3d).

Surface weather in Europe is related to the Euro-Atlantic regimes, and indeed this was one of the original motivations for their use (see Section 1). The above-discussed circulation anomalies conditioned on the North American regimes in turn have a clear footprint on the European surface weather associated with the Euro-Atlantic regimes (Figure 4, colors). The figure also displays the corresponding conditional T2m anomalies with respect to each Euro-Atlantic regime as contours. The AR T2m dipole, with negative anomalies in Western Europe and positive anomalies in Eastern Europe, shows significantly colder anomalies in Western Europe when associated with an ArH (Figure 4a). The Blk T2m dipole, with a warmer than usual Scandinavia and colder than usual central and southern Europe, displays a large zonal modulation for ArL and PT (Figure 4b). The former favors warmer temperatures in Western Europe and colder temperatures further East and North; the latter shows roughly inverse anomalies, with the warm anomalies coincident with, and on the northern flank of, the above-mentioned strengthened anticyclone over Scandinavia (Figure 3b). A further notable temperature modulation is the large region of significantly colder temperatures in Eastern Europe for NAO− co-occurring with PT (Figure 4d). A similar analysis can be conducted for precipitation (Figure S1 in Supporting Information S1). Significant signals are more limited than for T2m, and include a wetter than usual Iberia and Western France when the NAO+ co-occurs with AkR and a wetter Northern Germany/Poland when the NAO+ co-occurs with ArH. A number of other regional precipitation modulations are visible for other regime pairs, yet are not statistically significant. A larger sample size would be needed to draw robust conclusions on these.

4. Discussion and Conclusions

Weather regimes condense the large-scale atmospheric variability into a small number of recurrent and quasi-stationary patterns. Weather regimes defined over the Euro-Atlantic sector have seen an extensive use in the literature. Recently, North American weather regimes have been gaining momentum, for example, in the context of subseasonal forecasting (Molina et al., 2023; Robertson et al., 2020).

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

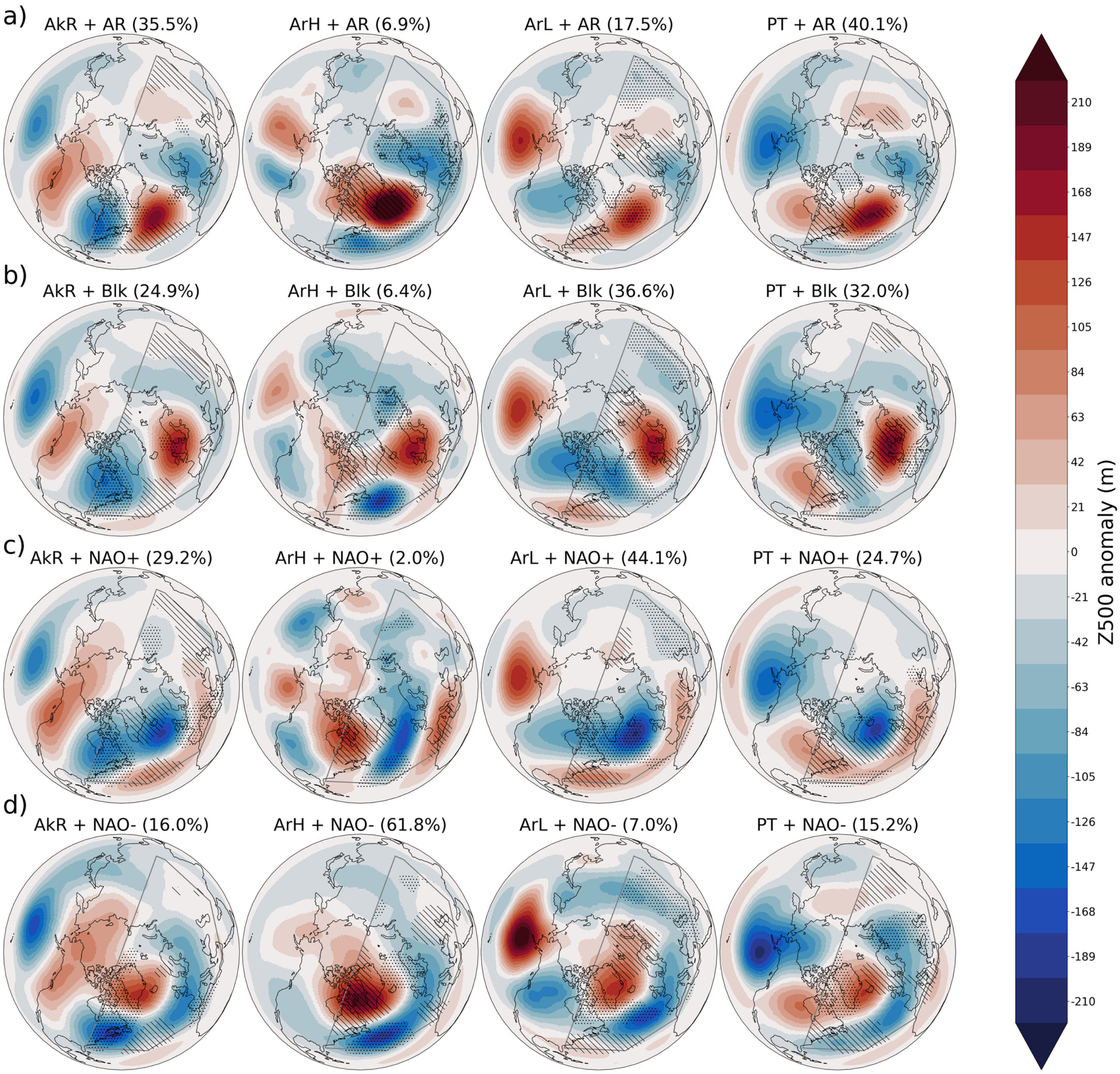

Figure 3. Composite 500 hPa geopotential height anomalies (Z500, m) when Euro-Atlantic regimes co-occur with each North American regime, with regime abbreviations as in Figure 1. Stippling and line hatching indicate significant negative (resp. positive) conditional anomalies relative to all occurrences of a given Euro-Atlantic regime. In both cases we use the 5% significance level, and only show significant anomalies within an extended Euro-Atlantic domain as marked by the gray boxes in each plot. Percentages in the plot titles display sample sizes relative to the total number of occurrences of the Euro-Atlantic regime shown in each row.

In this study, motivated by recently highlighted connections between the wintertime large-scale circulation and concurrent surface weather in the two continents (Davies, 2015; Kornhuber & Messori, 2023; Leeding et al., 2023; Messori & Faranda, 2023; Messori et al., 2016; Riboldi et al., 2023), we investigated the link between North American and Euro-Atlantic weather regimes. We found systematic links between the occurrence of specific North American and Euro-Atlantic regimes, with for example, ArH and NAO−, ArL and NAO+ and PT and AR showing a close co-variability. Additionally, when conditioning on the occurrence of North American regimes, the Euro-Atlantic regimes show large anomalies in occurrence frequency. In several cases, significant anomalies in occurrence frequencies persist at lags of up to ±15 days, suggesting that the joint analysis of the two sets of regimes can provide medium-range statistical predictability for anomalies in their occurrences. Given

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

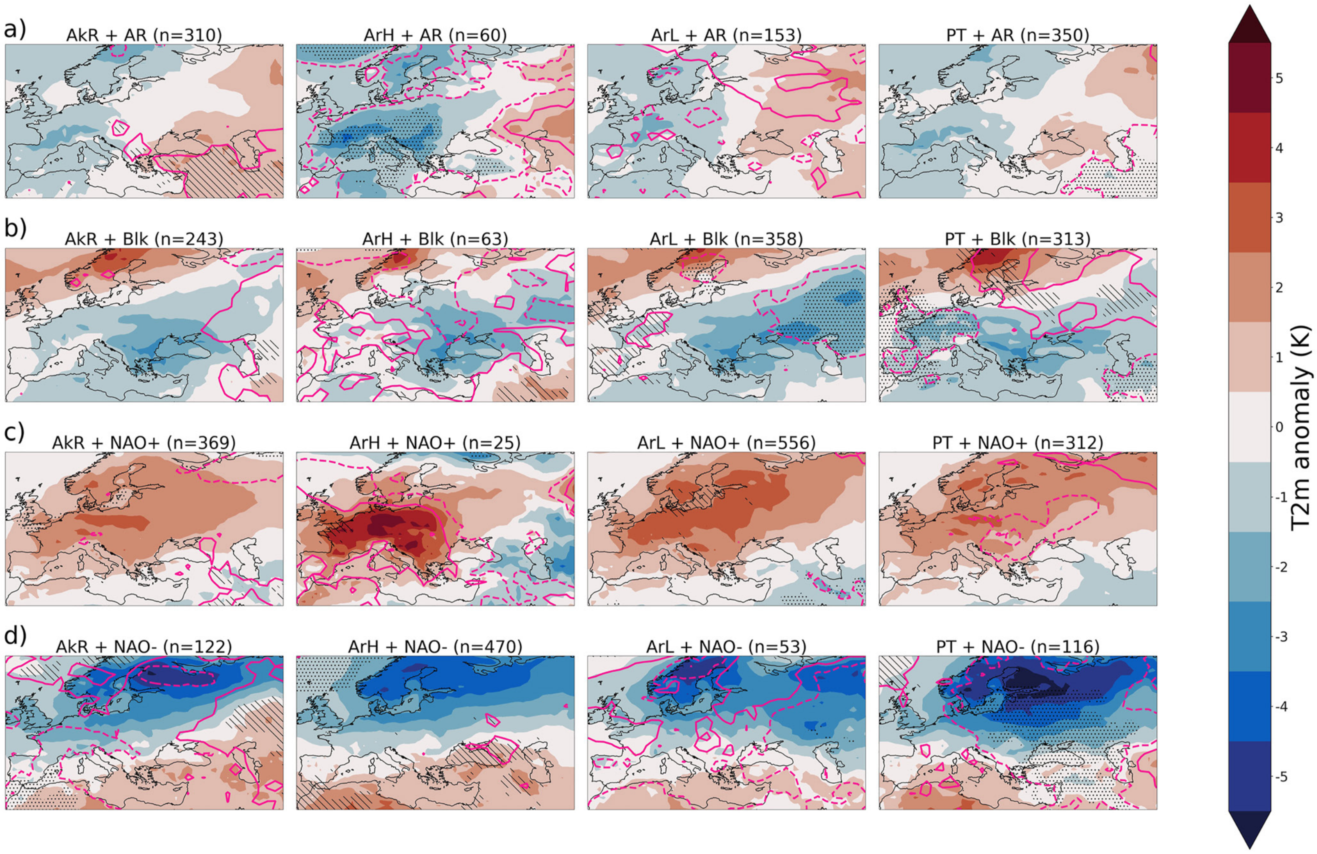

Figure 4. Composite 2-m temperature anomalies (T2m, K, colors) when Euro-Atlantic regimes co-occur with each North American regime, with regime abbreviations as in Figure 1. Corresponding conditional T2m anomalies (contours) relative to all occurrences of a given Euro-Atlantic regime. Continuous (dashed) contours show anomalies of +0.4 K (−0.4 K). Stippling and line hatching indicate significant negative (resp. positive) conditional anomalies at the 5% significance level. Numbers in the plot titles display sample sizes in days.

the use of weather regimes in the context of subseasonal predictability in both North America and Europe (e.g., Büeler et al., 2021; Cortesi et al., 2021; Molina et al., 2023; Robertson et al., 2020), such a link between the two sets of regimes may provide a novel predictability pathway. A promising line of future work would thus be to adopt jointly the two sets of regimes in subseasonal predictability studies.

We further find that the North American regimes correspond to large anomalies in the occurrence frequency of North Atlantic jet latitude regimes (Figure 2b). There is a known connection between the Euro-Atlantic regimes and jet regimes, with the AR preferentially matching a northern jet regime, the NAO+ matching a central jet and the NAO− matching a southern jet (Madonna et al., 2017). This is also reflected in the u850 anomalies in Figure 1b. Our results are broadly consistent with this picture. In agreement with Madonna et al. (2017), the ArH favors the occurrence of the NAO− and of the southern jet regime. Similarly, the ArL favors the occurrence of the NAO+ and of the central jet regime, and the PT of AR and of the northern jet regime. Nonetheless, we also obtain some less intuitive results. For example, the ArL and AkR regimes have different relations with the Euro-Atlantic regimes, yet their link to the jet regimes is similar, with both significantly favoring the central regime and significantly suppressing the southern regime (cf. Figures 2a and 2b). Akr favors a heightened frequency of AR occurrence; while the central jet regime is most frequently associated with the NAO+, it also occurs during some AR days (see Figure 8 in Madonna et al. (2017)). Moreover, AR conditional on AkR displays a southward-shifted ridge compared to the unconditional AR (Figure 3a), which is consistent with the fact that the Akr–AR combination likely preferentially falls into the subset of AR days displaying a central jet regime. This in turn may explain the fact that AkR favors a heightened frequency of the central jet regime. We conclude that the link between North American weather regimes and Atlantic jet latitude regimes is complex, and can be mediated by variations in the circulation associated with specific Euro-Atlantic weather regimes.

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10.1029/2023GL104696

Connected to this, we find significant anomalies in the large-scale circulation and the surface weather over Europe associated with the Euro-Atlantic regimes, when conditioning on North American regimes. This finding connects to the notion of a link between wintertime North American and European weather (Davies, 2015; De Luca et al., 2020; Kornhuber & Messori, 2023; Leeding et al., 2023; Messori & Faranda, 2023; Messori et al., 2016; Riboldi et al., 2023), yet its interpretation fundamentally differs from the event-based approach adopted in the above studies. Indeed, weather regimes occur frequently (typically on the order of 20%–30% of the time in a four-regime classification), making our findings relevant in a "typical weather" perspective rather than for a small number of carefully selected events.

Future work could investigate whether the interplay between North American and European regimes is also relevant in an extreme events perspective, and whether the relationship is bi-directional—namely whether conditioning on the Euro-Atlantic regimes may result in specific circulation and surface weather anomalies in North America. Correlations between closely linked regime pairs mostly peak at lag 0, thus evidencing no systematic time shift. Nonetheless, the intuitive picture is one of downstream causality from North American to Euro-Atlantic regimes, following the know role of propagating wave trains from the North Pacific in modulating the North Atlantic circulation (e.g., Franzke et al., 2004; Riviere & Orlanski, 2007; Schemm et al., 2018). Recent work has however argued for a complex and bidirectional link between North American and Euro-Atlantic circulation anomalies and surface extremes (Riboldi et al., 2023). This partly builds upon earlier literature outlining the potential upstream influence of the North Atlantic storm track on cold spells in the eastern United States (e.g., Dickson & Namias, 1976; Smith & Sheridan, 2019).

We have defined the North American and Euro-Atlantic weather regimes following the literature, since we sought to investigate the links between the different regimes as used in past studies. This implied using partially overlapping geographical domains for the two sets of weather regimes, and some of the links we identify may be ascribed to this overlap. For example, the correlation between continuous regime indices decreases markedly if these are defined on non-overlapping domains. We nonetheless note that the correlation results for non-overlapping domains are qualitatively consistent with those obtained for the overlapping domains. We further note that many of the circulation anomalies and all of the investigated surface anomalies conditioned on the North American regimes, occur well outside the region the latter regimes are defined on. Nonetheless, in a predictability perspective it may be interesting to conduct a future systematic investigation on the use of non-overlapping domains.

We conclude that there is a close connection between North American and Euro-Atlantic weather regimes. A joint analysis of the two sets of regimes may thus provide medium-range statistical predictability for anomalies in their occurrence frequencies. Conditioning on North American weather regimes further correspond to significant anomalies in the European surface weather associated with the Euro-Atlantic regimes. While the two sets of regimes have generally been treated separately in the literature, these links highlight the usefulness of analyzing them jointly.

Data Availability Statement

ERA5 data are freely available on both pressure levels (Hersbach et al., 2018a) and at the (near-)surface (Hersbach et al., 2018b) from the Copernicus Climate Change Service Climate Data Store.

Acknowledgments

GM and JD acknowledge the travel support of the International Meteorological Institute based at the Department of Meteorology of Stockholm University. GM acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant agreement no. 948309, CENÆ project). JD is funded as part of subproject T2 of the Transregional Collaborative Research Center SFB/TRR 165 "Waves to Weather" (https://www.wavestoweather.de, last accessed: 05/2023). Both authors thank two anonymous Reviewers and the Editor for their helpful input.

References

Ali, S. M., Martius, O., & Röthlisberger, M. (2021). Recurrent Rossby wave packets modulate the persistence of dry and wet spells across the globe. *Geophysical Research Letters*, *48*(5), e2020GL091452. https://doi.org/10.1029/2020gl091452

Alpert, P., Osetinsky, I., Ziv, B., & Shafir, H. (2004). Semi-objective classification for daily synoptic systems: Application to the eastern Mediterranean climate change. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *24*(8), 1001–1011. https://doi.org/10.1002/joc.1036

Barrier, N., Treguier, A.-M., Cassou, C., & Deshayes, J. (2013). Impact of the winter North-Atlantic weather regimes on subtropical sea-surface height variability. *Climate Dynamics*, *41*(5–6), 1159–1171. https://doi.org/10.1007/s00382-012-1578-7

Baur, F., Hess, P., & Nagel, H. (1944). *Kalender der grosswetterlagen europas 1881–1939* (Vol. 35). Bad Homburg.

Büeler, D., Ferranti, L., Magnusson, L., Quinting, J. F., & Grams, C. M. (2021). Year-round sub-seasonal forecast skill for Atlantic–European weather regimes. *Quarterly Journal of the Royal Meteorological Society*, *147*(741), 4283–4309. https://doi.org/10.1002/qj.4178

Cehelsky, P., & Tung, K. K. (1987). Theories of multiple equilibria and weather regimes—A critical reexamination. Part II: Baroclinic two-layer models. *Journal of the Atmospheric Sciences*, *44*(21), 3282–3303. https://doi.org/10.1175/1520-0469(1987)044<3282:tomeaw>2.0.co;2

Charney, J. G., & DeVore, J. G. (1979). Multiple flow equilibria in the atmosphere and blocking. *Journal of the Atmospheric Sciences*, *36*(7), 1205–1216. https://doi.org/10.1175/1520-0469(1979)036<1205:mfeita>2.0.co;2

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Cortesi, N., Torralba, V., Lledó, L., Manrique-Suñén, A., Gonzalez-Reviriego, N., Soret, A., & Doblas-Reyes, F. J. (2021). Yearly evolution of Euro-Atlantic weather regimes and of their sub-seasonal predictability. *Climate Dynamics*, *56*(11–12), 3933–3964. https://doi.org/10.1007/s00382-021-05679-y

Davies, H. C. (2015). Weather chains during the 2013/2014 winter and their significance for seasonal prediction. *Nature Geoscience*, *8*(11), 833–837. https://doi.org/10.1038/ngeo2561

De Luca, P., Messori, G., Pons, F. M., & Faranda, D. (2020). Dynamical systems theory sheds new light on compound climate extremes in Europe and eastern North America. *Quarterly Journal of the Royal Meteorological Society*, *146*(729), 1636–1650. https://doi.org/10.1002/qj.3757

Dickson, R. R., & Namias, J. (1976). North American influences on the circulation and climate of the North Atlantic sector. *Monthly Weather Review*, *104*(10), 1255–1265. https://doi.org/10.1175/1520-0493(1976)104<1255:naiotc>2.0.co;2

Domeisen, D. I., Grams, C. M., & Papritz, L. (2020). The role of North Atlantic–European weather regimes in the surface impact of sudden stratospheric warming events. *Weather and Climate Dynamics*, *1*(2), 373–388. https://doi.org/10.5194/wcd-1-373-2020

Dorrington, J., Strommen, K., & Fabiano, F. (2022). Quantifying climate model representation of the wintertime Euro-Atlantic circulation using geopotential-jet regimes. *Weather and Climate Dynamics*, *3*(2), 505–533. https://doi.org/10.5194/wcd-3-505-2022

Dorrington, J., Strommen, K., Fabiano, F., & Molteni, F. (2022). CMIP6 models trend toward less persistent European blocking regimes in a warming climate. *Geophysical Research Letters*, *49*(24), e2022GL100811. https://doi.org/10.1029/2022GL100811

Dorrington, J., & Strommen, K. J. (2020). Jet speed variability obscures Euro-Atlantic regime structure. *Geophysical Research Letters*, *47*(15), e2020GL087907. https://doi.org/10.1029/2020GL087907

Fabiano, F., Christensen, H., Strommen, K., Athanasiadis, P., Baker, A., Schiemann, R., & Corti, S. (2020). Euro-Atlantic weather regimes in the PRIMAVERA coupled climate simulations: Impact of resolution and mean state biases on model performance. *Climate Dynamics*, *54*(11–12), 5031–5048. https://doi.org/10.1007/s00382-020-05271-w

Fabiano, F., Meccia, V. L., Davini, P., Ghinassi, P., & Corti, S. (2021). A regime view of future atmospheric circulation changes in northern mid-latitudes. *Weather and Climate Dynamics*, *2*(1), 163–180. https://doi.org/10.5194/wcd-2-163-2021

Faranda, D., Masato, G., Moloney, N., Sato, Y., Daviaud, F., Dubrulle, B., & Yiou, P. (2016). The switching between zonal and blocked mid-latitude atmospheric circulation: A dynamical system perspective. *Climate Dynamics*, *47*(5–6), 1587–1599. https://doi.org/10.1007/s00382-015-2921-6

Fereday, D. (2017). How persistent are North Atlantic–European sector weather regimes? *Journal of Climate*, *30*(7), 2381–2394. https://doi.org/10.1175/jcli-d-16-0328.1

Franzke, C., Lee, S., & Feldstein, S. B. (2004). Is the North Atlantic oscillation a breaking wave? *Journal of the Atmospheric Sciences*, *61*(2), 145–160. https://doi.org/10.1175/1520-0469(2004)061<0145:itnaoa>2.0.co;2

Grams, C. M., Beerli, R., Pfenninger, S., Staffell, I., & Wernli, H. (2017). Balancing Europe's wind-power output through spatial deployment informed by weather regimes. *Nature Climate Change*, *7*(8), 557–562. https://doi.org/10.1038/nclimate3338

Hannachi, A., Straus, D. M., Franzke, C. L., Corti, S., & Woollings, T. (2017). Low-frequency nonlinearity and regime behavior in the Northern Hemisphere extratropical atmosphere. *Reviews of Geophysics*, *55*(1), 199–234. https://doi.org/10.1002/2015rg000509

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2018a). ERA5 hourly data on pressure levels from 1959 to present [Dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.bd0915c6

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2018b). ERA5 hourly data on single levels from 1959 to present [Dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hochman, A., Alpert, P., Harpaz, T., Saaroni, H., & Messori, G. (2019). A new dynamical systems perspective on atmospheric predictability: Eastern Mediterranean weather regimes as a case study. *Science Advances*, *5*(6), eaau0936. https://doi.org/10.1126/sciadv.aau0936

Hochman, A., Messori, G., Quinting, J. F., Pinto, J. G., & Grams, C. M. (2021). Do Atlantic-European weather regimes physically exist? *Geophysical Research Letters*, *48*(20), e2021GL095574. https://doi.org/10.1029/2021gl095574

Kidson, J. W. (2000). An analysis of New Zealand synoptic types and their use in defining weather regimes. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *20*(3), 299–316. https://doi.org/10.1002/(sici)1097-0088(20000315)20:3<299::aid-joc474>3.0.co;2-b

Kornhuber, K., & Messori, G. (2023). Recent increase in a recurrent pan-Atlantic wave pattern driving concurrent wintertime extremes. *Bulletin of the American Meteorological Society*, *104*(9), E1694–E1708. https://doi.org/10.1175/bams-d-21-0295.1

Lamb, H. (1950). Types and spells of weather around the year in the British Isles: Annual trends, seasonal structure of the year, singularities. *Quarterly Journal of the Royal Meteorological Society*, *76*(330), 393–429. https://doi.org/10.1002/qj.49707633005

Lee, S., Furtado, J., & Charlton-Perez, A. (2019). Wintertime North American weather regimes and the Arctic stratospheric polar vortex. *Geophysical Research Letters*, *46*(24), 14892–14900. https://doi.org/10.1029/2019gl085592

Leeding, R., Riboldi, J., & Messori, G. (2023). On pan-Atlantic cold, wet and windy compound extremes. *Weather and Climate Extremes*, *39*, 100524. https://doi.org/10.1016/j.wace.2022.100524

Lembo, V., Fabiano, F., Galfi, V. M., Graversen, R. G., Lucarini, V., & Messori, G. (2022). Meridional-energy-transport extremes and the general circulation of Northern Hemisphere mid-latitudes: Dominant weather regimes and preferred zonal wavenumbers. *Weather and Climate Dynamics*, *3*(3), 1037–1062. https://doi.org/10.5194/wcd-3-1037-2022

Madonna, E., Li, C., Grams, C. M., & Woollings, T. (2017). The link between eddy-driven jet variability and weather regimes in the North Atlantic-European sector. *Quarterly Journal of the Royal Meteorological Society*, *143*(708), 2960–2972. https://doi.org/10.1002/qj.3155

Mallet, P.-E., Claud, C., & Vicomte, M. (2017). North Atlantic polar lows and weather regimes: Do current links persist in a warmer climate? *Atmospheric Science Letters*, *18*(8), 349–355. https://doi.org/10.1002/asl.763

Messori, G., Caballero, R., & Gaetani, M. (2016). On cold spells in North America and storminess in western Europe. *Geophysical Research Letters*, *43*(12), 6620–6628. https://doi.org/10.1002/2016gl069392

Messori, G., & Faranda, D. (2023). On the systematic occurrence of compound cold spells in North America and wet or windy extremes in Europe. *Geophysical Research Letters*, *50*(7), e2022GL101008. https://doi.org/10.1029/2022gl101008

Messori, G., Harnik, N., Madonna, E., Lachmy, O., & Faranda, D. (2021). A dynamical systems characterisation of atmospheric jet regimes. *Earth System Dynamics*, *12*(1), 233–251. https://doi.org/10.5194/esd-12-233-2021

Messori, G., Kretschmer, M., Lee, S. H., & Wendt, V. (2022). Stratospheric downward wave reflection events modulate North American weather regimes and cold spells. *Weather and Climate Dynamics*, *3*(4), 1215–1236. https://doi.org/10.5194/wcd-3-1215-2022

Michel, C., & Rivière, G. (2011). The link between Rossby wave breakings and weather regime transitions. *Journal of the Atmospheric Sciences*, *68*(8), 1730–1748. https://doi.org/10.1175/2011jas3635.1

Michelangeli, P.-A., Vautard, R., & Legras, B. (1995). Weather regimes: Recurrence and quasi stationarity. *Journal of the Atmospheric Sciences*, *52*(8), 1237–1256. https://doi.org/10.1175/1520-0469(1995)052<1237:wrraqs>2.0.co;2

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Molina, M. J., Richter, J. H., Glanville, A. A., Dagon, K., Berner, J., Hu, A., & Meehl, G. A. (2023). Subseasonal representation and predictability of North American weather regimes using cluster analysis. *Artificial Intelligence for the Earth Systems*, *2*(2), e220051. https://doi.org/10.1175/aies-d-22-0051.1

Parker, T., Woollings, T., Weisheimer, A., O'Reilly, C., Baker, L., & Shaffrey, L. (2019). Seasonal predictability of the winter North Atlantic oscillation from a jet stream perspective. *Geophysical Research Letters*, *46*(16), 10159–10167. https://doi.org/10.1029/2019gl084402

Riboldi, J., Leeding, R., Segalini, A., & Messori, G. (2023). Multiple large-scale dynamical pathways for pan–Atlantic compound cold and windy extremes. *Geophysical Research Letters*, *50*(10), e2022GL102528. https://doi.org/10.1029/2022gl102528

Riddle, E. E., Stoner, M. B., Johnson, N. C., L'Heureux, M. L., Collins, D. C., & Feldstein, S. B. (2013). The impact of the MJO on clusters of wintertime circulation anomalies over the North American region. *Climate Dynamics*, *40*(7–8), 1749–1766. https://doi.org/10.1007/s00382-012-1493-y

Riviere, G., & Orlanski, I. (2007). Characteristics of the Atlantic storm-track eddy activity and its relation with the North Atlantic Oscillation. *Journal of the Atmospheric Sciences*, *64*(2), 241–266. https://doi.org/10.1175/jas3850.1

Robertson, A. W., & Ghil, M. (1999). Large-scale weather regimes and local climate over the western United States. *Journal of Climate*, *12*(6), 1796–1813. https://doi.org/10.1175/1520-0442(1999)012<1796:lswral>2.0.co;2

Robertson, A. W., Vigaud, N., Yuan, J., & Tippett, M. K. (2020). Toward identifying subseasonal forecasts of opportunity using North American weather regimes. *Monthly Weather Review*, *148*(5), 1861–1875. https://doi.org/10.1175/mwr-d-19-0285.1

Schemm, S., Rivière, G., Ciasto, L. M., & Li, C. (2018). Extratropical cyclogenesis changes in connection with tropospheric ENSO teleconnections to the North Atlantic: Role of stationary and transient waves. *Journal of the Atmospheric Sciences*, *75*(11), 3943–3964. https://doi.org/10.1175/jas-d-17-0340.1

Seabold, S., & Perktold, J. (2010). Statsmodels: Econometric and statistical modeling with python. In *Proceedings of the 9th python in science conference* (Vol. 57, pp. 10–25080).

Smith, E. T., & Sheridan, S. C. (2019). The influence of atmospheric circulation patterns on cold air outbreaks in the eastern United States. *International Journal of Climatology*, *39*(4), 2080–2095. https://doi.org/10.1002/joc.5935

van der Wiel, K., Bloomfield, H. C., Lee, R. W., Stoop, L. P., Blackport, R., Screen, J. A., & Selten, F. M. (2019). The influence of weather regimes on European renewable energy production and demand. *Environmental Research Letters*, *14*(9), 094010. https://doi.org/10.1088/1748-9326/ab38d3

Vautard, R. (1990). Multiple weather regimes over the North Atlantic: Analysis of precursors and successors. *Monthly Weather Review*, *118*(10), 2056–2081. https://doi.org/10.1175/1520-0493(1990)118<2056:mwrotn>2.0.co;2

Vigaud, N., Robertson, A. W., & Tippett, M. K. (2018). Predictability of recurrent weather regimes over North America during winter from submonthly reforecasts. *Monthly Weather Review*, *146*(8), 2559–2577. https://doi.org/10.1175/mwr-d-18-0058.1

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., et al. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2

Wilks, D. (2016). "The stippling shows statistically significant grid points": How research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin of the American Meteorological Society*, *97*(12), 2263–2273. https://doi.org/10.1175/bams-d-15-00267.1

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*(649), 856–868. https://doi.org/10.1002/qj.625

Yang, S., Yuan, H., & Dong, L. (2022). Offshore wind resource assessment by characterizing weather regimes based on self-organizing map. *Environmental Research Letters*, *17*(12), 124009. https://doi.org/10.1088/1748-9326/aca2c2

Yiou, P., & Nogaj, M. (2004). Extreme climatic events and weather regimes over the North Atlantic: When and where? *Geophysical Research Letters*, *31*(7), L07202. https://doi.org/10.1029/2003gl019119

19448007, 2023, 21, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104696 by Karlsruher Institution F. Technologie, Wiley Online Library on [09/11/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License