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Explaining Pan-Atlantic Cold and Windy Extremes Using an Analog-Based Approach

Jacopo Riboldi[1,2], Joshua Dorrington[3,4], Meriem Krouma[1], Richard Leeding[1], and Gabriele Messori[1,5,6]

[1]Department of Earth Sciences, Uppsala University, Uppsala, Sweden, [2]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland, [3]Department Troposphere Research (IMKTRO), Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, [4]Geophysical Institute, University of Bergen (UiB), Bergen, Norway, [5]Swedish Centre for Impacts of Climate Extremes (climes), Uppsala University, Uppsala, Sweden, [6]Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

Jacopo Riboldi and Joshua Dorrington contributed equally to this work.

Key Points:

- Spatially compounding pan-Atlantic extremes are flow-dependent, an issue that can be tackled using circulation analogs
- The majority of pan-Atlantic compound extremes can be explained by the influence of the shared North Atlantic and/or stratospheric circulation
- Strong westerly Rossby wave trains are an exception, causally linking deep North American troughs to later European wind extremes

Supporting Information:

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

Correspondence to:

J. Riboldi,
jacopo.riboldi@env.ethz.ch

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Author Contributions:

Conceptualization: Jacopo Riboldi, Joshua Dorrington, Gabriele Messori
Data curation: Jacopo Riboldi, Joshua Dorrington, Richard Leeding
Formal analysis: Jacopo Riboldi, Joshua Dorrington, Meriem Krouma, Richard Leeding
Funding acquisition: Gabriele Messori
Investigation: Jacopo Riboldi, Joshua Dorrington
Methodology: Jacopo Riboldi, Joshua Dorrington, Meriem Krouma, Richard Leeding

Abstract The occurrence of cold spells over different regions of North America has been previously linked to windy extremes over Western Europe. These so-called pan-Atlantic extremes are necessarily mediated by the North Atlantic circulation. It is known that the Atlantic storm track modulates European windstorm occurrence, but it is unclear whether the American cold spells directly influence the storm track, or whether the cooccurrence of extremes is indirect—a result of a common large-scale driver. In this study, cold spells over both central North America and northeast Canada are clustered with respect to the evolution of the large-scale circulation over the North Atlantic. The direct contribution of cold spells to the European wind extremes is then ascertained using circulation analogs, so that different states of the North Atlantic storm track can be compared for days with and without cold spells. Consistent with previous work, two main pathways emerge from the analysis, called "zonal" and "wavy" for simplicity. For a wavy pathway, North American cold spell occurrence is directly associated with more frequent European wind extremes than expected from the Euro-Atlantic flow, as a result of Rossby wave trains. For the other pathways, the common driver of storm track variability linked to the anomalous Atlantic circulation was sufficient to explain more frequent wind extremes across Europe, with no or little ascertainable contribution from the cold spells. This analysis clarifies that the causality of wintertime pan-Atlantic extremes is flow-dependent—either direct or indirect depending on the active dynamical pathway.

Plain Language Summary Cold extremes over North America and wind extremes over Europe tend to cooccur; thanks to specific large-scale circulation patterns over the North Atlantic. Such patterns, however, could in principle favor the occurrence of European wind extremes even in the absence of North American cold spells. The question becomes then how much the occurrence of the cold extremes contributes to the wind extremes over Europe. To answer this question, we develop a new method to isolate the circulation patterns favoring the cooccurrence of winter extremes over different North American and European regions. After having defined those events, we look for days where the flow over the North Atlantic resembles such patterns but does not involve the presence of an upstream cold spell. The relative importance of cold spell occurrence for European extremes is then determined with respect to those "analog days," which provide a benchmark. The results vary for different patterns and regions, but the effect of cold spells on European wind extremes becomes visible if anomalous circulations from the North Pacific sector are involved in their dynamics. By leveraging the power of circulation analogs, this approach can help to ascertain if and how upstream extremes can systematically affect downstream ones.

1. Introduction

Different extreme weather events often cooccur in geographically distant regions. If this cooccurrence is a result of a causal, physical mechanism, rather than simple chance, then the distinct extreme events can be considered as part of a single "spatially compounding" extreme event (Zscheischler et al., 2020). This type of compound event can lead to impacts, which are greater than the sum of impacts from the different extremes if they had occurred individually. Spatially compounding extremes can expose financial and public actors to highly correlated losses when assets and properties are damaged across multiple regions in a short time (Gagliardi et al., 2022; Mills, 2005) threatening, for instance, global crop yields (e.g., Kornhuber et al., 2023).

Resources: Meriem Krouma, Richard Leeding
Software: Richard Leeding
Supervision: Gabriele Messori
Visualization: Jacopo Riboldi, Joshua Dorrington
Writing – original draft: Jacopo Riboldi, Joshua Dorrington
Writing – review & editing: Jacopo Riboldi, Joshua Dorrington, Meriem Krouma, Richard Leeding, Gabriele Messori

Despite the expectations of a heightened impact of compound events in a future climate (e.g., Ridder et al., 2022), determining the physical mechanism connecting separate extremes is challenging. From a purely dynamical point of view, different weather systems can be connected through the propagation of Rossby waves, complemented by the action of eddy/mean flow feedbacks (e.g., Drouard et al., 2015; Rivière & Drouard, 2015). Furthermore, the spatial compounding of the different extremes might be flow-dependent, in the sense that the known patterns of subseasonal flow variability (such as the ones related to the state of the stratospheric polar vortex, e.g., Domeisen & Butler, 2020; Finke et al., 2023; Jiménez-Esteve & Domeisen, 2020) can modulate their occurrence. Such complex interactions result in multiple “pathways” of connection between extremes, related to different mechanisms and relevant at different times (e.g., Köhler et al., 2023; Riboldi et al., 2023). This paper investigates the flow-dependence and physical mechanisms of pan-Atlantic cold and windy extremes, a type of spatially compounding extreme that features cooccurring cold spells over North America and windstorms over Europe during boreal winter.

Following the winter of 2013/14, which featured extreme cold over eastern North America and was at the same time among the stormiest winters recorded in the British Isles (Huntingford et al., 2014; Kendon & McCarthy, 2015; Knight et al., 2017), Messori et al. (2016) quantified the systematic cooccurrence of North American cold spells and European wet and windy extremes, a result confirmed by other recent studies (De Luca et al., 2020; Leeding et al., 2023b; Messori & Faranda, 2023). The downstream circulation anomalies associated with North American cold spells emerge both in the large-scale flow and at synoptic scales, and affect the intensity and tracks of extratropical cyclones over Europe and the North Atlantic (Leeding et al., 2023a).

However, North American cold spells can result from multiple distinct large-scale circulations, with differing impacts over Europe. Two main pathways connecting North American cold spells to European extreme winds have been heuristically identified by Riboldi et al. (2023): one where the propagation of Rossby wave trains from the North Pacific to the North Atlantic leads to an intensification of the upper-level jet stream and to wind impacts over the British Isles and a second involving an upper-level anticyclone over Greenland tied to an equatorward displacement of the North Atlantic eddy-driven jet stream, thereby leading to extreme winds over the Iberian Peninsula even before the occurrence of the cold spell. In Riboldi et al. (2023), however, pathways were based on a simple subdivision of cold spells over a smaller region of North America, and the number of cold spells in each pathway was determined ad hoc using terciles of wave-activity flux (WAF) anomalies over the cold spell region. In this study, we aim to identify the pathways driving pan-Atlantic cold and windy extremes more systematically, allowing for a future generalization of our approach to different compound extremes.

Consideration of these pathways raises the question of whether pan-Atlantic extremes are simply the result of a large-scale North Atlantic flow that favors both upstream cold spells and downstream windy extremes, or whether the unique circulation associated with the cold spells steers the downstream circulation directly. To distinguish these two cases, we can look for significant atmospheric anomalies corresponding to cold spells, *relative to specific states of the North Atlantic*, rather than to the overall climatology. To perform this operation, we borrow from extreme event attribution science the approach of large-scale flow analogs (e.g., Faranda et al., 2022, 2023; Ginesta et al., 2023; Jézéquel et al., 2018). We use these analogs to disentangle the contribution of the cold spell-related circulation pattern to extreme winds over Europe, separating it from the effect of the concomitant state of the North Atlantic storm track. Large-scale flow analogs have already proven useful in studying the dynamics of extreme events: two examples are the study by Pohorsky et al. (2019), who isolated from extratropical variability the impact of recurving North Atlantic tropical cyclones onto downstream European extreme precipitation events and the study by Lucarini et al. (2023), who used flow analogs to study the typicality of the 2021 Western North American heat wave.

We describe the data and analytical methods used in Section 2, followed by a description of the cold spell pathways we identify in Section 3 and of their relation to the large-scale circulation and European wind extremes in Section 4. Discussion and conclusions are presented in Section 5.

2. Data and Methods

The whole analysis is based on the ERA5 reanalysis data set (Hersbach et al., 2020) by the European Centre for Medium-Range Weather Forecasts, with a spatial resolution of 0.5°× 0.5° and a temporal resolution of 1 day. While ERA5 has been extended back to 1940, reanalyses exhibit divergent regime statistics prior to the satellite era (Dorrington, 2021), and so we sidestep this issue by using data only between November 1979 and March 2021. Daily mean values are obtained from the average of four 6-hourly time steps (00, 06, 12, 18UTC).

2.1. Cold Spell Definition

Cold spells are determined for two target regions; central North America (CNA; 105°W–80°W, 35°N–50°N) and northeastern Canada (NEC; 80°W–60°W, 50°N–65°N). We divide both regions into 5 × 5° cells (i.e., a 3 × 5 grid for CNA and 3 × 4 for NEC) and compute for each cell the daily mean, area-averaged 2-m temperature anomaly for the extended winter period (NDJFM), skipping cells that contain <50% land (cells for each regions are shown in Figures S4 and S5 in Supporting Informtion S1). Anomalies are defined with respect to a 30-year climatology smoothed with a 5-day running mean, with the 30-year period centered on the given year: years near the start or the end of the analysis period use the 1979–2008 and 1992–2021 climatologies, respectively (as in Leeding et al., 2023b). The first percentile of surface temperature anomalies in each cell is determined for each calendar day from the distribution formed by drawing all temperature anomalies within a 7-day window centered on the calendar day and from all years (similar to Leeding et al., 2023b). Each percentile is therefore determined from $41 \times 7 = 287$ values. Then, the cell is assigned a value of 1 for days where the daily mean, area-averaged temperature anomaly falls below the first percentile (cold event), else it is assigned 0. Thus, we produce for CNA and NEC a binary data set detailing extreme low temperature occurrences at 15 and 8 possible points (after cell exclusions), respectively, for all days considered in the analysis period. A scalar binary event index is then defined, keeping any day where at least three of the points experienced a cold event, separated in time by at least 6 days from a preceding or subsequent cold event. This results in 58 and 41 events for the CNA and NEC regions, respectively; for each cold spell, the day featuring the lowest area-averaged temperature anomaly is defined as the cold spell peak time t_{CS}.

2.2. Pathway Clustering

We outline here an approach to classify North American cold spells, starting from the evolution of the North Atlantic circulation and from the eventual presence of Rossby wave trains over North America in the days preceding and following the cold spells themselves. The state of the North Atlantic circulation and the presence of Rossby wave trains were discussed by Riboldi et al. (2023) as discriminating factors to separate pan-Atlantic cold and windy extremes in different "pathways," and thus provide a physical explanation to the statistical cooccurrence between extremes discussed by Messori et al. (2016) and Leeding et al. (2023b).

The circulation over the Euro-Atlantic sector can be succinctly described by three geopotential-jet regime patterns, defined as in Dorrington et al. (2022); they were used to construct three continuous weather regime indices, following the approach introduced by Michel et al. (2012). These regimes capture the dominant anticyclonic flows over the Atlantic: a Greenland blocking/NAO- pattern, an Atlantic Ridge (AR), and a European blocking (BLK), shown in Figure S1 in Supporting Information S1. The standardized regime indices measure the activity of each regime on any given day, with negative index values corresponding to the cyclonically dominated antipatterns: an NAO+, Atlantic trough and European trough state. As such, these three indices provide a concise summary of Euro-Atlantic flow variability. The group propagation of quasi-stationary Rossby waves is diagnosed using the WAF diagnostic by Takaya and Nakamura (1997), computed at several vertical levels (see Text S1 in the Supporting Informtion S1 for more details). A scalar WAF index representing Rossby wave propagation over North America is obtained by averaging the magnitude of horizontal WAF at 250 hPa over the CNA region.

As the life cycles of the cold spells can extend for several weeks, we choose to consider the values of the four aforementioned indices over a range of ±10 days around the day of each cold spell's minimum temperature. By stacking sequential dates, we produce a $4 \times 21 = 84$ dimension state space (3 weather regime indices, 1 WAF index, and 21 days), in which each data point completely characterizes the 3-week evolution of the regime and WAF indices around each cold spell date (Figure 1a). The dimensionality of this space is then reduced using principal component analysis, keeping only the two leading PCs and clustering them into two components using the k-means algorithm, as in Michelangeli et al. (1995); Ferranti et al. (2015); and Dorrington and Strommen (2020) (Figure 1b; the first two empirical orthogonal functions for NEC and CNA explain, respectively, 43.5% and 42.6% of the variance and are shown in Figure S2 in Supporting Information S1). We refer to this approach as pathway clustering. Two clusters were selected for each of the two considered regions (i.e., CNA and NEC), to match the same number of pathways identified for CNA cold spells by Riboldi et al. (2023). The

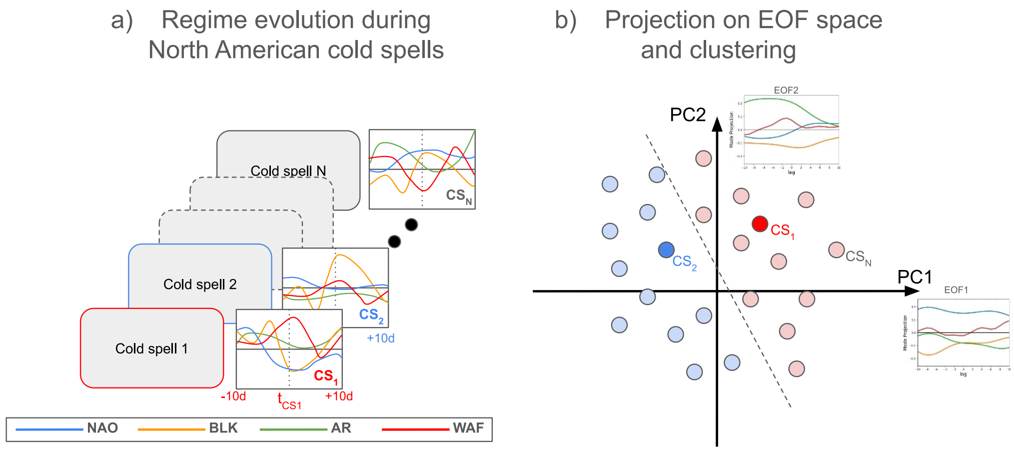

Figure 1. Illustration of the pathway clustering approach. (a) Matching of each cold spell with the corresponding time evolution of the geopotential/jet weather regimes (NAO, BLK, and AR) and of the wave-activity flux indices over central North America in the time window encompassing ±10 *d* with respect to the day of the cold spell peak t_{CS}. (b) Determination of the first two empirical orthogonal functions and projection of each cold spell on the space spanned by them. Cluster analysis is then conducted at the corresponding t_{CS} (large dots) to attribute each event to a pathway.

resulting clustering is also insensitive to changes in the number of principal components retained between two and ten, with qualitatively similar pathways obtained in all cases (not shown).

2.3. Dynamical Indices

In order to analyze the multifaceted dynamics of pan-Atlantic cold and windy extremes, we use a number of scalar dynamical indices, defined as follows:

Jet speed and latitude. Following Parker et al. (2019), we compute the zonal mean of daily zonal wind over the Atlantic sector 0°W–60°W and take a 9-day rolling average. We then identify the latitude between 15°N and 75°N at which the wind is maximum for each day, and refer to this latitude as jet latitude and the corresponding maximum wind value as jet speed.

Upper- and lower-level polar vortex. Zonal mean zonal wind at 60°N and at the 10 hPa and 100 hPa levels was used to define indices of the upper- and lower-level stratospheric polar vortex, respectively.

Reflection index. The possible role of stratospheric wave reflection for North American cold spells is evaluated using the index by Messori et al. (2022). It is computed as the difference between the standardized meridional eddy heat flux $(v'T')^*$ at 100 hPa, averaged over Siberia (140°E–200°E) and Canada (130°W–80°W) between 45°N and 75°N. Eddy quantities v' and T' are determined by removing the zonal mean from the corresponding field at each time step. Wave reflection events are thus linked to positive values of the index, corresponding to above average upward wave propagation over Siberia and simultaneous enhanced downward propagation over Canada.

Destructive wind. Destructive winds are defined as grid point daily maximum 10-m winds exceeding the local 98th percentile, determined over all years with a 30-day running window (following Klawa & Ulbrich, 2003). This Boolean field was then spatially averaged over two separate regions (depicted in Figures S4 and S5 in Supporting Informtion S1) to obtain scalar indices that represent the fraction of the domain affected by extreme wind on each day: the first over the western portion of the Iberian Peninsula (9°W–6°W, 36°N–44°N) and the second over the central portion of the British Isles (10°W–0°W, 51°N–59°N). A centered rolling 7-day mean is then applied to define a daily index.

2.4. Definition of Flow Analogs and Analog Significance

Throughout our paper, we compute the statistical significance of deviations from climatology by random resampling (1,000 times with repetition), creating synthetic cold spell time series, and using those to produce associated null composites. However, North American cold spells tend to occur during already anomalous flow regimes (e.g., Lee et al., 2019; Lee et al., 2023; Millin et al., 2022) that even without a cold spell might be conducive to more widespread European extremes than climatology. Furthermore, when splitting cold spells into pathways, significant deviations from climatology may not necessarily be related to the occurrence of the cold spell, but could instead merely be an artifact of the clustering process. For example, as we use the evolution of the NAO regime index to define our clusters, any preferred NAO phase in one pathway or another cannot be causally linked to the cold spells. A similar reasoning holds for the stratospheric indices, which are themselves correlated to the NAO.

We address those problems through the use of flow analogs, which were obtained following the approach detailed in Krouma et al. (2022). First, the daily average 250-hPa geopotential height anomaly at t_{CS} over the North Atlantic domain [80°W–40°E, 30°N–90°N] was computed for each cold spell in a given pathway and a region. Analogs were then sought among the daily 250-hPa height anomaly fields during the extended winter months (NDJFM) between 1979 and 2021, excluding the days within 15 days of a cold spell. For each pathway and region, then, the 25 days that have the smallest RMS error with respect to the corresponding North Atlantic composite are taken as the flow analogs. To further avoid temporal correlation and ensure analogs are spread across the considered time period, analog days are not allowed to come from the same extended winter as the cold spell date. This approach allows us to focus on the role of the North Atlantic storm track in engendering the European wind extremes, as the 250-hPa level is commonly used to diagnose storm track activity, while ensuring that the influence of cold spells is minimized.

Having defined flow analogs, we then test whether anomalies associated with cold spells are statistically different from those associated with flow analogs, using a *t* test. Significant differences between cold spell composites and the flow analog composites might indicate a direct connection to the cold spell itself, and is the closest we can come to identifying causal links in this purely observational study. In order to distinguish clearly the two complementary significance tests we use, we shall refer to usual significance tests with respect to climatology as significance, and to the one assessed with respect to flow analogs as analog significance. For clarity, the three cases of significance are as follows:

Significant but not analog significant. Even though the feature (e.g., the occurrence of extreme winds over a given region) is anomalous with respect to the climatology, the occurrence of the cold spell did not directly contribute to it. The anomaly is then rather explained by the background circulation pattern across the North Atlantic that indirectly causes both the anomalous feature and the cold spell (i.e., acts as a confounder).

Analog significant but not significant. The influences of the cold spell and the background circulation on the feature are opposite, leading to anomalies that are not outside the climatological range of variability.

Both significant and analog significant. The feature is directly affected by the large-scale circulation specifically tied to the cold spell, which alters the evolution of the North Atlantic background circulation expected from the analogs.

3. Characterizing Pathways of Pan-Atlantic Cold and Windy Extremes From Clustering and Analogs

3.1. Clustered Pathways

Cluster analysis is employed to identify the main pathways for pan-Atlantic cold and wind extremes over the two considered CNA and NEC regions. In both regions, cold spells separate into a "Zonal" and a "Wavy" pathway, a useful heuristic that we will maintain throughout the paper. The clustering results in the attribution of 23 cold spells to CNA-Zonal, 35 to CNA-Wavy, 25 to NEC-Zonal, and 16 to NEC-Wavy. The different numbers indicate that the pathways do not occur with the same frequency, but that CNA-Zonal and NEC-Wavy are around 50% of the times less common than, respectively, CNA-Wavy and NEC-Zonal.

The CNA-Zonal pathway is characterized by an equatorward-displaced North Atlantic jet stream, while positive geopotential anomalies are found at higher latitudes (Figure 2a). The CNA-Wavy pathway, on the other hand, features a Rossby wave train propagating across North America, ranging from a ridge over Alaska to a trough over the Northeastern US and another ridge over the central North Atlantic (Figure 2b). The two CNA pathways show a clear correspondence to the ones described in Riboldi et al. (2023): CNA-Zonal, with weakened geopotential height gradients over the North Atlantic, corresponds to their Euro-Atlantic dipole pathway, while CNA-Wavy,

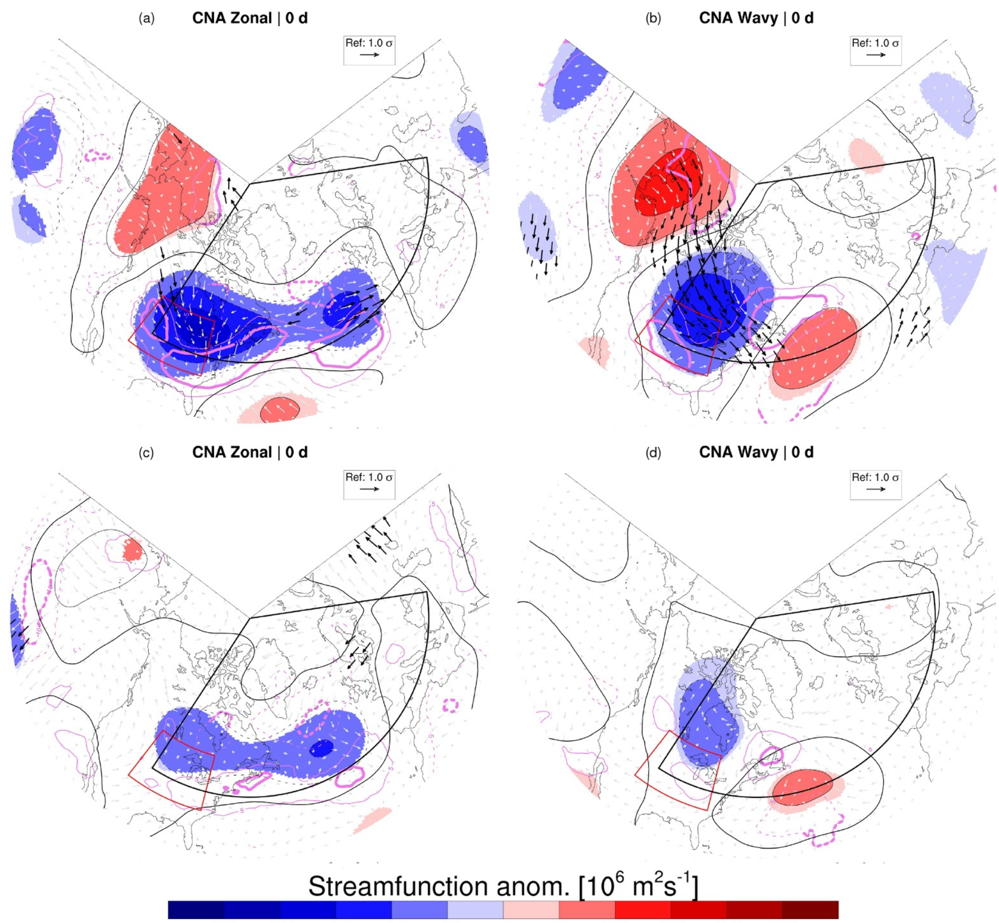

Figure 2. Composites of low-pass filtered (10 days cutoff) standardized anomalies of wave-activity flux (WAF) (arrows), low-pass filtered geostrophic stream function anomalies (black contours), and wind speed anomalies (magenta contours, only ±5 m s^{-1}, ±10 m s^{-1}, negative values dashed) at 250 hPa for the (a) 23 cold spells assigned to CNA-Zonal, and the (b) 35 cold spells assigned to the CNA-Wavy subsets at t_{CS} (central North America region encompassed by the red box). (c and d) Composites of the best analog for the same subsets. Analogs are computed from the 250-hPa geopotential pattern over the sector surrounded by the bold black line (80°W–40°E, 40°N–90°N) as in Krouma et al. (2022). Vectors featuring a significantly higher module of WAF anomaly (computed as in Riboldi et al., 2023) are plotted in black. Stream function anomalies are shaded, and 250-hPa wind anomalies are indicated with a thicker magenta contour, only when significant with respect to the top 99% and bottom 1% of a 10,000-time randomly resampled distribution.

with its pronounced westerly WAF anomalies, matches their Rossby wave train pathway. Cooccurrence of European extreme wind events—over the northern tip of the Iberian Peninsula before the CNA-Zonal cold spells and over northern Europe both prior to and following CNA-Wavy cold spells—also matches the composites by Riboldi et al. (2023), as shown in Figure S4 in Supporting Information S1.

The NEC-Zonal cold spells show a clear Arctic low pattern with northerly flow over Eastern Canada, and a steeper geopotential gradient over the location of the west Atlantic jet, reinforcing it (Figure 3a). In contrast, the NEC-Wavy regime shows relatively minor stream function anomalies, with a meridionally oriented jet stream associated with a high-latitude wave train over the North Atlantic (Figure 3b). Such a wave train does not feature significant horizontal WAF anomalies over North America, possibly due to a rapid zonal propagation that the 10-day low-pass filter, upon which the computation of WAF is based, cannot capture effectively (see Takaya & Nakamura, 1997). Despite this difference, the presence of a meridionally amplified flow over the considered sector remains evident when looking at the pattern of zonal wind anomalies (Figure 3b). NEC-zonal events tend to cooccur with, or follow soon after, elevated destructive wind in the UK and over northern Europe, while the NEC-

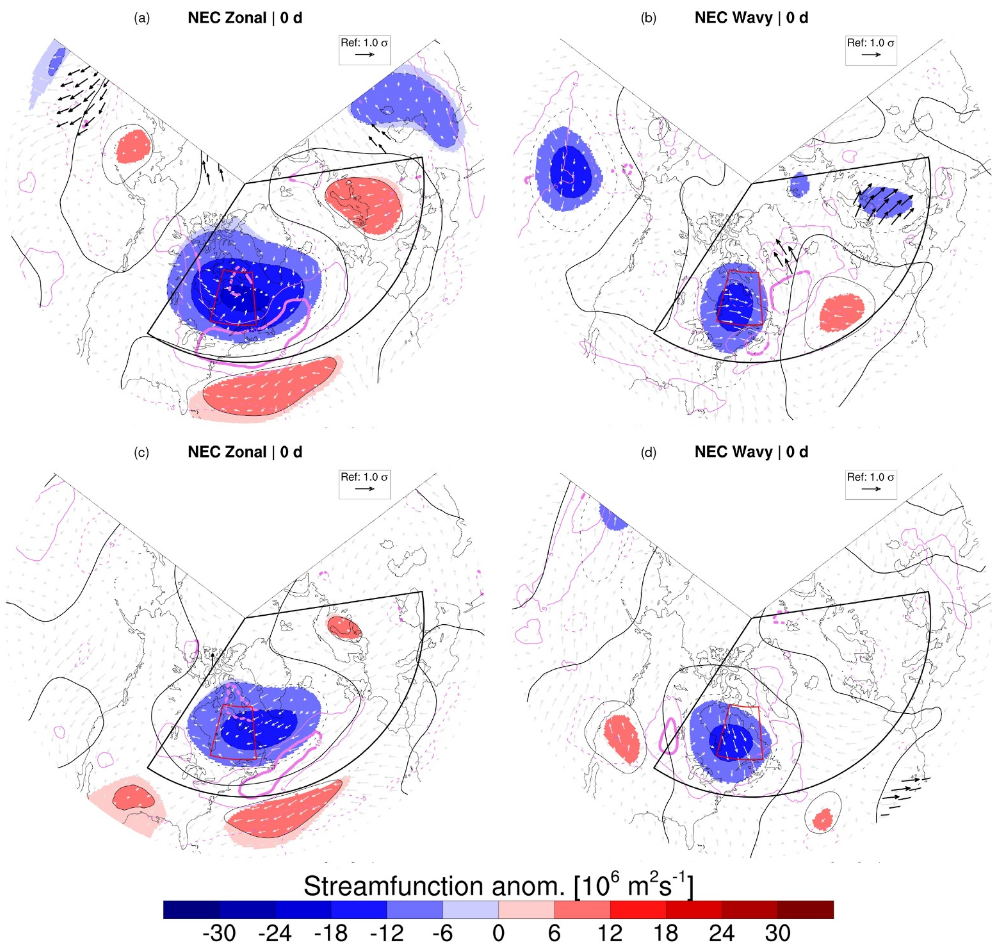

Figure 3. As in Figure 2, but for the (a) 25 cold spells assigned to NEC-Zonal and the (b) 16 cold spells assigned to the NEC-Wavy subsets at t_{CS} (northeastern Canada region encompassed by the red box) (c) and (d) Composites of the best analogs for the same subsets.

Wavy pathway shows elevated destructive wind over the Mediterranean in the week following cold spells, but with limited impact over land (see Figure S5 in Supporting Informtion S1).

3.2. Analogs

The composites of analogs for each cold spell pathway allows us to better understand the unique role of North American cold spells in inducing anomalous North Atlantic and European weather. The analogs do not feature cold spells over the considered CNA and NEC regions, while at the same time, they closely resemble the large-scale circulation during cold spells. Where this is not the case, it indicates that a given flow feature rarely occurs without a North American cold spell, that is, it can be considered part of the "cold-spell inducing circulation" rather than of the broader large-scale circulation. On the other hand, if the analog-based composite resembles the event-based one, the occurrence of the cold spells is likely not substantially affecting the North Atlantic circulation: this can be inferred because "normal" variability—in the absence of cold spells—can produce analogous flow patterns to the ones observed over the North Atlantic during upstream cold spells.

The composite of analogs of CNA-Wavy cold spells features notably weaker anomalies over North America than the ones observed for CNA-Wavy cold spells themselves (compare Figure 2d with Figure 2b), with no significant WAF anomalies, which represent the propagation of a Rossby wave train from the North Pacific toward the Atlantic sector. The fact that analogs are not able to reproduce the wave train indicates that the observed response of the North Atlantic storm track is specific to the occurrence of CNA-Wavy cold spells, pointing toward a physical connection between them and European extremes. This planetary-scale feature has been specifically

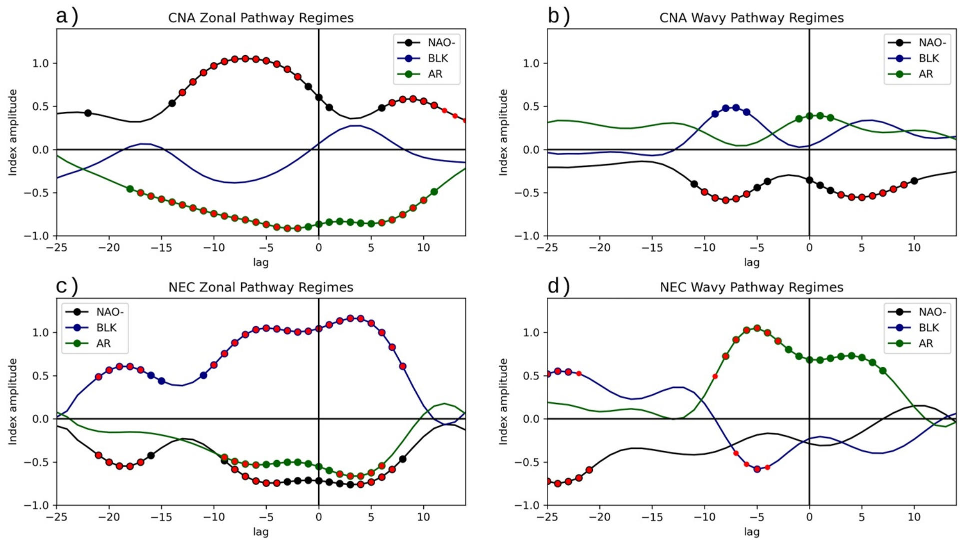

Figure 4. The life cycles of geopotential-jet regime indices during clustered North American cold waves over (a and b) central North America and (c and d) northeastern Canada regions. Solid lines show the mean value of each index, composited in time relative to t_{CS}. Colored dots indicate significant anomalies ($p \leq 0.05$) with respect to the annual climatology, estimated by resampling. Red dots mark days where the corresponding index is significant with respect to the analogs (again $p \leq 0.05$) according to a Mann-Whitney U test.

linked to the occurrence of CNA cold extremes (e.g., Messori et al., 2016; Riboldi et al., 2023; Xie et al., 2017). A qualitative evaluation of the other analog composites suggests that they feature overall weaker anomalies than their corresponding cold spell pathways (Figures 2c, 3c, and 3d) but show similarities with the corresponding event composites also outside the target region for analogs. In such cases, the state of the North Atlantic storm track is closely connected to the upstream circulation producing the cold spell. This is in contrast with the CNA-Wavy pathway, where the knowledge of the state of the North Atlantic, captured by the analogs, does not constrain the upstream circulation, for example, the strong Alaskan ridge seen in the event composites (Figure 2b).

4. Mechanisms and Dynamics of Pan-Atlantic Cold and Windy Extremes

4.1. Regime Evolution

From a regime perspective, CNA-Zonal cold spells are associated with a persistent NAO- flow state: this regime peaks in amplitude 7 days prior to the cold spell, persists for 10 days afterwards and starts to break down from days 1–4 as the deep trough associated with the cold spell propagates East over Greenland (Figure 4a; see also Figure S3 in Supporting Informtion S1). The associated strong negative projection onto the AR regime is tied to the East Atlantic trough visible in Figure 2a. Both regime anomalies are significantly larger than those of the climatology and analog flow states in the weeks preceding and following the cold spell, indicating that CNA-Zonal cold spells are associated with exceptionally persistent and high-amplitude weather regimes. Conjecturally, the persistence of such anomalies may favor the formation and advection of polar air necessary to induce cold extremes. From the Pacific side, a pronounced Alaskan ridge forms 7 days before the cold spell, and peaks in magnitude 3 days before (Figure 5a). Its significance with respect to the analogs indicates that the state of the North Atlantic storm track alone is not capable of inducing CNA-Zonal cold spells, but also needs an upstream ridge (although weaker than CNA-Zonal) to favorably amplify the flow over North America. This observation is consistent with synoptic experience, as the occurrence of a negative NAO pattern is often not a sufficient condition to bring cold weather over the eastern portion of North America.

In contrast, CNA-Wavy cold spells feature far weaker Euro-Atlantic regime anomalies, and with the opposite sign (Figure 4b): a period of positive NAO flow states is observed 12–16 days before the cold spell, which is significant also with respect to analogs. During the cold spells themselves, the low geopotential height anomalies over Greenland shift southwest and form a trough over North America (Figure 2b). This trough is more zonally

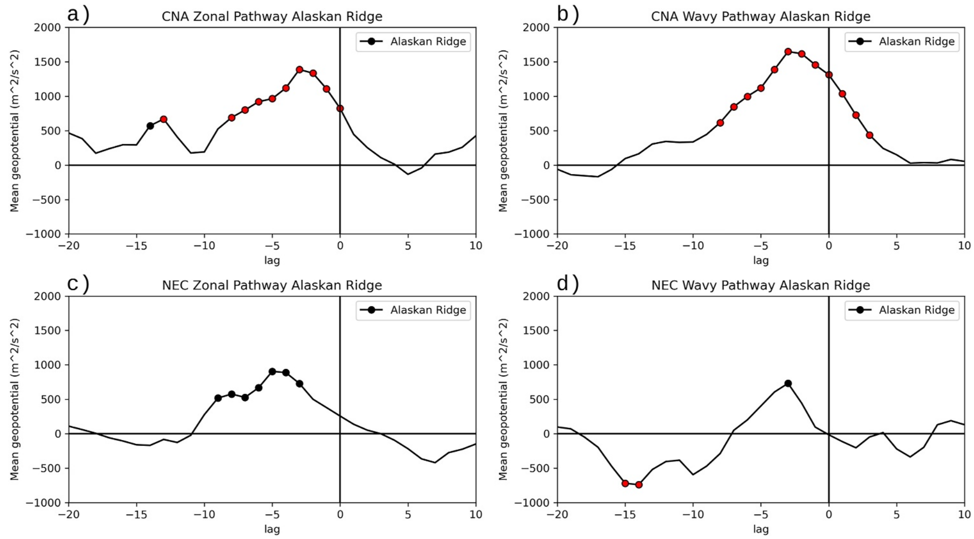

Figure 5. As in Figure 4 but for geopotential height anomalies averaged over the Alaskan region [55°N–72°N, 1700°W–140°W].

confined than in the CNA-Zonal pathway, with an AR regime anomaly in the Euro-Atlantic sector, and again with a prominent Alaskan ridge anomaly, which peaks 3 days before the cold spells (Figure 5b). The CNA trough and the temporarily weakened Euro-Atlantic regime structure are more persistent in the CNA-Wavy regime than for CNA-Zonal. In both cases, however, a significant redevelopment of the Euro-Atlantic precursor flow, not explicable via the analogs, occurs in the week following the events.

NEC cold spells also naturally divide into a Zonal and a Wavy pathway, but with very different regime dynamics from their CNA equivalents. The NEC-Zonal pathway shows strong and persistent regime anomalies both with respect to climatology and to flow analogs (Figure 4c). The apparent contradiction of large positive projections onto the BLK regime in this Zonal pathway is resolved by noticing that the large-scale flow is near-zonal from the east of North America to the Mid-Atlantic, thus projecting onto an NAO+ flow, but also features a trough in the East Atlantic and strong anticyclonic anomalies over Europe, which project at the same time onto a BLK geopotential/jet regime. NEC-Zonal cold spells feature a significantly enhanced Alaskan ridge, though of smaller magnitude than for CNA (Figure 5c). The lack of significance with respect to the analogs, however, indicates that its appearance is not strictly related to the cold spell occurrence.

The NEC-Wavy pathway features a preexisting AR regime, which is strongest 5 days before the cold spell, and is much more pronounced than in analogs (Figure 4d). This corresponds to a trough over northern Europe, and thus to opposite regime anomalies to NEC-Zonal. As indicated by the lack of significance with respect to the analogs, the occurrence of NEC-Wavy cold spells does not influence the evolution of North Atlantic weather regimes; thus, the cold spells in this pathway appear to be a "passive" response to the larger-scale dynamics. Also, they are associated with the weakest Alaskan ridge signature of all the considered pathways (Figure 5d).

In summary, all the cold spell pathways are embedded within multiweek patterns of Euro-Atlantic and North Pacific large-scale variability. For the NEC cold spells, a high-level synthesis places this large-scale flow as the first mover, setting the stage for a cold spell, whereas CNA cold spells can also drive the downstream Atlantic flow. Carefully unraveling this web of causal interactions is the aim of the rest of this paper.

4.2. Jet Indices

Cold spells in the CNA-Zonal pathway are characterized by an equatorward-displaced jet stream (Figure 6a). The significant early southward shift of the jet stream for CNA-Zonal cold spells, from 22 days before the cold spell, clearly precedes the development of the regime precursors, suggesting that the jet may be the driver of regime shifts, at least in this context. The equatorward jet shift around the actual occurrence of CNA-Zonal cold spells, on

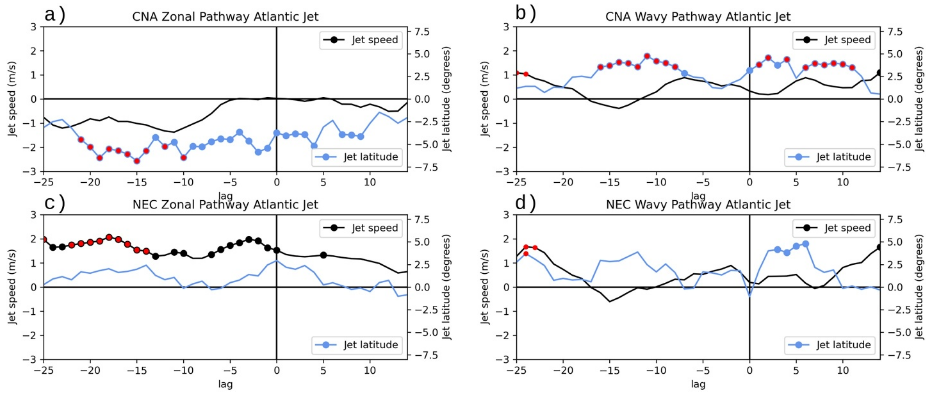

Figure 6. As in Figure 4, but for the evolution of the North Atlantic jet stream during clustered North American cold waves over (a and b) central North America and (c and d) northeastern Canada regions.

the other hand, seems solely due to the state of the North Atlantic circulation, as indicated by the lack of significance with respect to the analogs.

On the other hand, CNA-Wavy cold spells are tied to a poleward-displaced jet stream, which again precedes the shifts in regimes, but persists here for more than 10 days after the cold spells. The significance with respect to large-scale circulation analogs both before and after the cold spell might indicate a causal feedback, where a poleward jet favors upstream cold spell formation, which then in turn reinforces the poleward jet anomaly.

The jet evolution is again different for NEC cold spells. The occurrence of NEC-Zonal cold spells is preceded by a stronger than usual North Atlantic jet stream, located at the climatological, central latitude (Figure 6c), with significant anomalies in the previous 2 weeks. The presence of persistent jet speed anomalies might indicate a slow-moving pattern featuring enhanced geopotential gradients over the North Atlantic, likely related to the NAO+/BLK+ configuration (Figure 4c).

No robust jet anomalies precede the development of NEC-Wavy cold spells, although a northerly jet anomaly occurs in the week following the cold spell (Figure 6d). This is consistent with the AR projection of the flow analogs (Figure 4d), which corresponds to a meridionally oriented North Atlantic jet.

4.3. Stratosphere

The CNA-Zonal pathway features a suppression of the polar vortex in the 20–40 days preceding cold spell peak, which propagates down to the lower stratosphere by lag −25 (Figure 7a). This temporally coincides with the southern deflection of the jet stream for the same pathway, visible roughly 3 weeks before cold spell peak time (Figure 6a). Such anomalies are consistent with the analog flow, and with the known connection between the

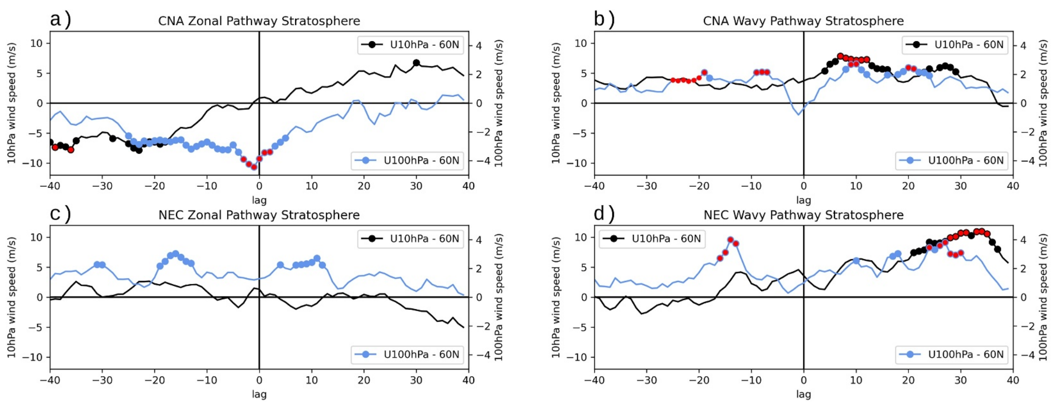

Figure 7. As in Figure 4, but for the evolution of the stratospheric polar vortex during clustered North American cold waves over (a and b) central North America and (c and d) northeastern Canada regions.

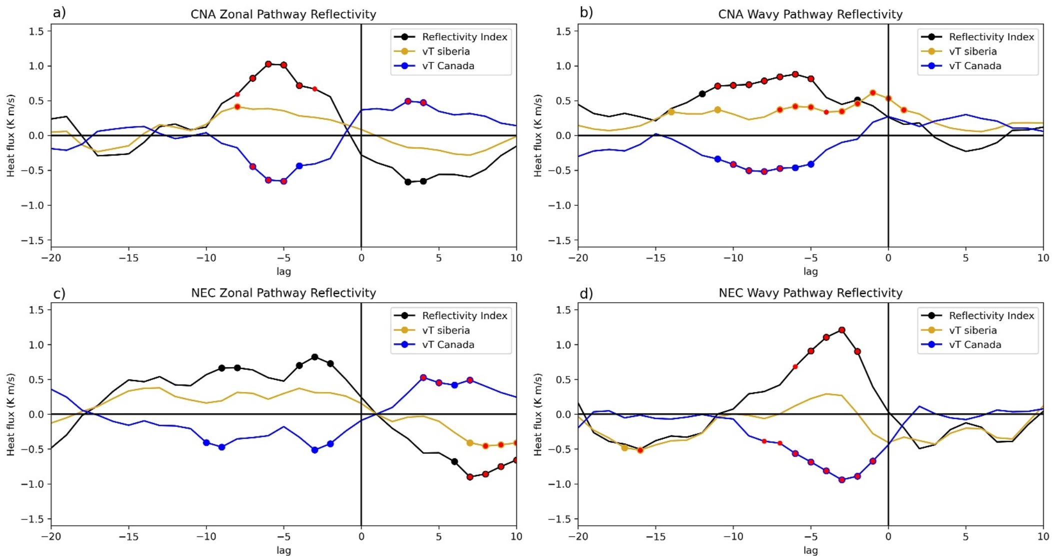

Figure 8. Time series of averaged reflection index (black contour), defined as the difference between 100-hPa standardized meridional eddy heat averaged over Siberia (blue contour) and Canada (yellow contour), for the considered (a) CNA-Zonal, (b) CNA-Wavy, (c) NEC-Zonal, and (d) NEC-Wavy cold spells. Black and red dots indicate significance with respect to the climatology and with respect to the analogs, as in Figure 4.

weak state of the stratospheric polar vortex and a preference for a negative NAO state (e.g., during sudden stratospheric warming events; Baldwin & Dunkerton, 1999). Downward-propagating zonal wind anomalies from the stratosphere to the stratosphere indeed precede CNA-Zonal cold spells (cf. Figure S6a in the Supporting Informtion S1). The weakened polar vortex in the preceding weeks might then be related to a southerly shift of the eddy-driven jet, such as the one observed before CNA-Zonal cold spells, and to the onset of an NAO- regime, hence providing the background state of low geopotential height over the CNA region that favors this pathway's development. Significantly weakened 100-hPa zonal wind anomalies can also be seen in the days around the cold spell peak (lag 0), likely as a result of the stronger than normal NAO- regime over the North Atlantic (visible in Figure 4a).

The CNA-Wavy pathway has little stratospheric preconditioning, although slightly strengthened vortex conditions can be seen, particularly in the lower stratosphere (Figure 7b). Here, however, there seems to be a clear effect of the cold spell occurrence onto the stratosphere, with a significantly strengthened polar vortex in the 5 to 30 days following the cold spell. The significance with respect to flow analogs suggests that such an intensification is a consequence of the circulation specifically associated with the cold spell development (see also Figure S6b in Supporting Informtion S1). Therefore, the difference between pathways can be seen not only in the surface extremes but also in the upper atmospheric circulation.

As the occurrence of North American cold spells had been related to the phenomenon of stratospheric downward reflection of Rossby waves, we employed the wave reflection index by Messori et al. (2022) to assess its possible role (Figure 8). The examination of the index yields mixed impressions. In fact, only the anomalously high reflection index in CNA-Wavy is related to persistent heat flux anomalies in both the Siberian and the Canadian sectors (Figure 8b), while for other regions and pathways, such anomalies are mostly driven by the heat fluxes in the Canadian sector only. In agreement with Messori et al. (2022), the cold spells peak at the end of periods with a high reflection index (Figure 8). However, Messori et al. (2022) found a stretching and partial weakening of the polar vortex following the onset of reflection events; here, we find that following the peak of the cold spells, the polar vortex is stronger than average. This apparent discrepancy may stem from the fact that the analysis in Messori et al. (2022) focuses on persistent and intense reflection events, which may display different characteristics from the days with positive reflection index values that we consider here. Moreover, the reflection events defined in Messori et al. (2022) exhibit a large spread in how the strength of the polar vortex evolves throughout individual events.

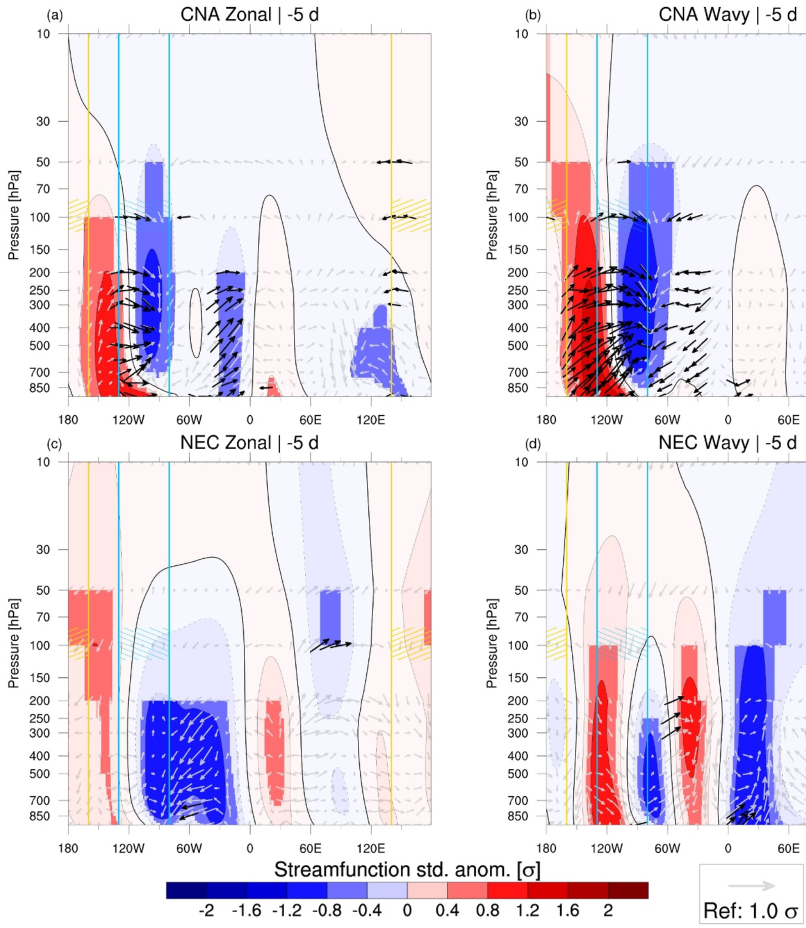

Figure 9. Composite of wave-activity flux std. anomaly cross-sections for (a and b) central North America, and (c and d) northeastern Canada cold spell pathways. The plots result from 10-day averages centered 5 days before cold spell peak time and from a latitudinal average between 40°N and 80°N. Opaque shading and black arrows indicate statistical significance with respect to climatology ($p \leq 0.01$). The longitudes of the two regions used to compute the wave reflection index by Messori et al. (2022) are marked by yellow (Siberia) and cyan (Canada) lines.

Complementing the reflection index, cross-sections of vertical WAF indicate significant anomalies in the troposphere and the lower stratosphere in the 10 days preceding CNA-Wavy events, with an upward flux in the region of the Alaskan ridge and downward fluxes over North America, especially in the upper troposphere (Figure 9b; in the lower troposphere, conversely, the cold spell results in positive heat and WAF). A similar pattern of WAF anomalies, although weaker, is present for CNA-Zonal (Figure 9a). The WAF pattern in CNA-Wavy, however, is slightly different from the one discussed by Messori et al. (2022), with anomalies mostly localized over the North Pacific and North America (Figure S7 in Supporting Informtion S1), suggesting that the dynamics might not be that of a pure reflection event.

Less clear stratospheric signatures emerge for NEC pathways. The strengthened 100-hPa vortex visible 3 weeks before NEC-Zonal events likely reflects the development of the previously discussed, early NAO+ regime precursor (Figure 7c). The broad trough over the western North Atlantic is also visible in the cross-sections as a mainly tropospheric feature, and is not associated with significant anomalies in vertical WAF (Figure 9c). A strengthening of the vortex similar to the CNA-Wavy pathway is also observed for NEC-Wavy, but larger in amplitude and at a later lead time—more than 3 weeks after the cold spell (Figure 7d). While here we cannot explain exactly how such a long response would manifest, one hypothesis is that the high-latitude wave train associated with NEC-Wavy would project on higher wave numbers than the ones efficiently propagating to the stratosphere (Figure 9d), leading to a reduction in vertical wave propagation and to polar vortex strengthening. This hypothesis is supported by the analysis of the dominant wave numbers over the Northern Hemisphere, which

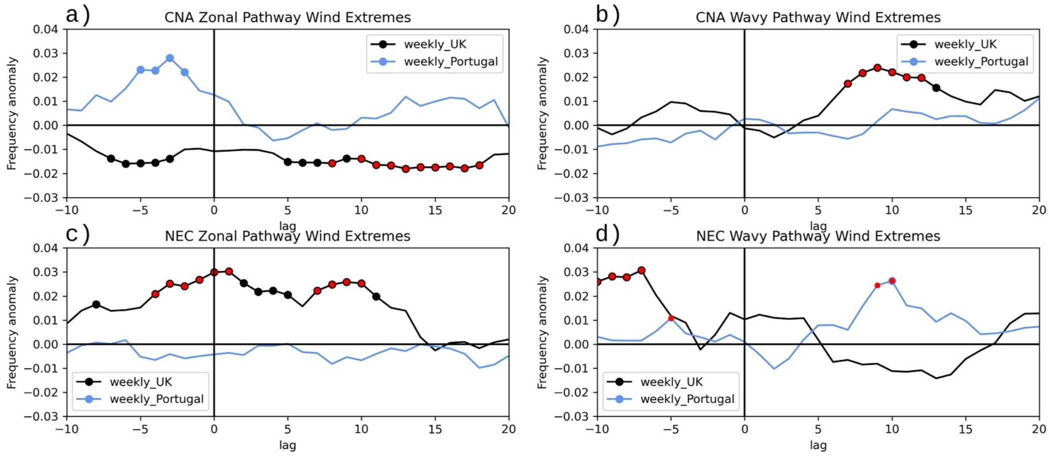

Figure 10. The evolution of extreme wind at 10 m during clustered North American cold waves over (a and b) central North America, and (c and d) northeastern Canada regions.

exhibits positive anomalies for wave numbers 3–5 during NEC-Wavy cold spells (see Text S3 and Figure S8 in Supporting Informtion S1).

4.4. European Wind Extremes

As discussed in Section 3, CNA cold spells correspond to windy extremes in different European regions. However, for the CNA-Zonal pathway, the enhanced risk of Portuguese windstorms in the days before cold spells (Figure 10a) is not significant with respect to analogs. This result is consistent with the hypothesis outlined by Leeding et al. (2023b) and Riboldi et al. (2023) for this pan-Atlantic cold-windy pathway: the retrograding circulation pattern over the North Atlantic is indeed the responsible of the anticipated windy extremes over Iberia, rather than the North American cold spells. The CNA-Zonal cold spells are also associated with a reduced frequency of wind extremes over the British Isles, both before and after the cold spell (Figure 10a), consistent with the dominant NAO- regime over the North Atlantic (Figure 4a). The persistent NAO- might be related to the weaker than usual stratospheric polar vortex in the weeks preceding CNA-Zonal cold spells (Figure 7a), and with the suppression of wind extremes over the British Isles remaining visible for the 2–3 weeks following the cold spell (consistent with Afargan-Gerstman et al., 2024). Furthermore, the additional significance with respect to the analogs might indicate a reinforcement of the NAO- pattern by the cold spells themselves (Figure 10a; see also the second peak of the NAO- regime in Figure 4a).

The situation is different for the CNA-Wavy pathway, which features a significant increase in the frequency of windstorms over the British Isles 1–2 weeks after cold spell peak (Figure 10b). The significance with respect to the analogs indicates that the circulation pattern associated with the cold spells is decisive in causing such a heightened frequency of extreme wind, via a poleward shift in the North Atlantic jet stream (Figure 6b). The different downstream response in terms of wind extremes highlights the need for disaggregation of events: CNA cold spells actively suppress UK wind extremes in zonal Atlantic conditions, and actively amplify them in wave-dominated Atlantic conditions.

In the NEC-Zonal pathway, high extreme wind anomalies for the UK are also seen following the cold spell, as well as in the preceding week (Figure 10c). Here, the connection can be primarily understood in terms of the flow analogs, that is, the preexisting NAO+ flow state associated with the formation of cold spells of this type. The increased frequency of wind extremes over the British Isles in the week preceding NEC-Wavy cold spells can also be explained by flow analogs (Figure 10d). There is also a short-lived increase in wind extremes over the west coast of the Iberian Peninsula 10 days after the cold spell, contrary to the coincident poleward-displaced jet and the prevailing NAO+ flow pattern. Those wind extremes are related to the decay of the AR pattern (Figure 4d) and to the elongation of a trough over the Iberian Peninsula (not shown), features that seem to be peculiar to the evolution of NEC-Wavy cold spells—as indicated by the significance with respect to analogs. The effect of NEC-Wavy cold spells onto downstream wind extremes over Europe, however, cannot be ascertained as clearly as for the CNA-Wavy pathway.

Table 1
A Summary of Key Features of Each Cold Spell Pathway Discussed in Sections 3 and 4

Pathway	Large-scale flow regime	Destructive wind (and role of upstream cold spell)	Tropospheric features, preceding	Tropospheric features, following	Stratospheric features
CNA-Zonal	NAO-, weak Alaskan Ridge	Amplified in Portugal beforehand (common driver). Suppressed in UK after (direct influence)	NAO-, weak Alaskan ridge, and equatorward-displaced North Atl. jet	Atlantic trough, Alaskan ridge, and southern Atl. jet.	Weak vortex and high reflectivity before
CNA-Wavy	N. American wave train	Amplified in UK after (direct influence)	NAO+/BLK, strong Alaskan ridge, and poleward-displaced North Atl. jet	NAO+ and northern Atl jet	High reflectivity before and strong vortex after
NEC-Zonal	West Atlantic trough	Amplified in UK before and after (direct influence)	NAO+/BLK, fast North Atl. jet.	NAO+/BLK	High reflectivity before and strong lower vortex before and after
NEC-Wavy	Weak Atlantic wave train	–	Atlantic Ridge	Atlantic Ridge and poleward-displaced North Atl. jet.	High reflectivity 4–5 days before and strong vortex 20+ days after.

Note. Refer to Figures 2–8 and their discussion for precise details.

5. Conclusions and Outlook

The dynamics of spatially compounding pan-Atlantic cold and windy extremes has been the object of this work, with the aim of disentangling the impact that cold spells actually exert onto the North Atlantic circulation from the background atmospheric variability of the basin. The temporal evolution of the large-scale circulation anomalies that precede and follow North American cold spells has been taken into account and assessed using a novel "pathway clustering" approach, resulting in the identification of different pathways of connection between weather extremes. Analogs of the corresponding North Atlantic circulation in the absence of cold spells have been identified to isolate the direct impacts of cold spell-inducing flows on Western European extreme wind. Two North American regions are considered, both featuring a statistical connection with European extremes: the CNA region analyzed by Riboldi et al. (2023) and the NEC region discussed by Leeding et al. (2023b). To help the reader, Table 1 briefly summarizes the most relevant dynamical features identified for each pathway.

Pathway clustering using $n = 2$ clusters highlights the presence of a "zonal" pathway and of a "wavy" pathway for pan-Atlantic cold and windy extremes in both regions considered. Zonal pathways are associated with weather regimes resembling the North Atlantic Oscillation, and with frequency changes in European extreme wind events preceding the cold spells themselves. On the other hand, wavy pathways (in particular, CNA-Wavy) are associated mainly with eastward-propagating Rossby wave trains or more in general with a meridionally amplified flow, and with wind impacts that temporally follow the North American cold spells. The different pathways are reflected in distinct Euro-Atlantic weather regimes projections and opposite North Atlantic jet latitude and speed anomalies. Furthermore, we notice that some pathways seem to be more common than others: the CNA-Wavy pathway seems to occur 50% more frequently than CNA-Zonal (35 vs. 23 events, respectively), while NEC-Zonal is 50% more frequent than NEC-Wavy (25 vs. 16 events). Such inferences are, however, always limited by the smaller sample size.

The analysis of analogs of the North Atlantic circulation suggests that at least some of the wind impacts over Europe recorded around the cold spell date are actually due to the state of the North Atlantic in the days preceding the cold spell, rather than to a dynamical role played by the cold spell itself (e.g., by the enhancement of baroclinicity). This does not hold for the CNA-Wavy pathway, which features a doubling of extreme wind occurrences over the British Isles following the cold spell, as a direct result of the eastward propagating wave train associated with the cold spell. For the other three pathways, European wind impacts appear to be a result of large-scale drivers shared with the cold spells: a weak stratospheric polar vortex and subsequent Greenland blocking (CNA-Zonal), a deep Arctic low and strong central jet (NEC-Zonal), and an AR formed as part of a high-latitude wave train (NEC-Wavy).

The implications of these findings can be clarified with an example. CNA-Zonal cold spells are statistically associated with windstorms over Portugal, yet the latter can be explained simply by the same North Atlantic circulation pattern in place during the cold spells (sampled by the analogs); hence, it would be inappropriate to say that the occurrence of the North American cold extreme made an actual difference in the unfolding of the European wind extreme. On the other hand, the increase in frequency of wind extremes over the British Isles after CNA-Wavy cold spells cannot be reproduced by the analogs. This observation suggests that the occurrence of CNA-Wavy cold spells is directly related to a rare large-scale flow pattern, which also favors the occurrence of the European wind extremes. Our analysis thus confirms the systematic statistical cooccurrence between cold spells over North America and wind extremes in Europe and most importantly, proposes different causal connections to explain such cooccurrences.

While we have studied two pathways for each region, this was an a priori choice made for simplicity and to obtain robust statistics while using only the most reliable observational data. Future work exploring hundreds to thousands of years of extremes, for example, using the "unseen" approach (Thompson et al., 2017), could identify possible further dynamical pathways for cold spells. Based on our work, we identify a well-resolved stratosphere, Euro-Atlantic regimes, and teleconnections mediated by Rossby wave trains as minimum requirements for any model used for such a purpose. Future work could also consider the role of oceanic and tropical drivers, which have not been treated here.

The pathways we uncover have a strong projection onto the NAO. As the NAO is known to exhibit substantial interdecadal variability (Weisheimer et al., 2017), which also leads to interdecadal regime variability (Dorrington et al., 2022), this suggests similar interdecadal variability may be seen in the US cold spell-EU wind extreme teleconnection. While this goes beyond the scope of this work, such nonstationarity could perhaps also be accounted for through an appropriate pathway decomposition.

In conclusion, the diversity of relationships with differing causalities and sometimes opposite signs (e.g., suppressed vs. amplified UK wind following CNA-Zonal and CNA-wavy pathways, respectively) emphasizes the challenges of understanding the physical drivers of spatially compounding extremes, and cautions against assuming that pairs of extremes with relatively similar surface footprints should be connected by a single dynamical pathway. It also highlights the complexity of validating model representation of spatially compounding extremes and of leveraging these dynamical insights for practical prediction. Large-scale process-oriented approaches, such as those we put forward here, can play a key role for meeting these challenges, and for developing a deep dynamical understanding of spatially compounding extreme events.

Data Availability Statement

ERA5 hourly data from 1979 are available for several pressure levels (Hersbach et al., 2018a) and surface variables (Hersbach et al., 2018b). Both data sets were freely downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (https://doi.org/10.24381/cds.bd0915c6 and https://doi.org/10.24381/cds.adbb2d47). NAO data are available from the Climate Prediction Center of the National Oceanic and Atmospheric Administration, at the address https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml.

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