

1                    **Multiple large-scale dynamical pathways for**  
2                    **pan–Atlantic compound cold and windy extremes**

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8                    **Key Points:**

- 9                    • North American cold extremes and European windy extremes can be connected  
10                    physically by two distinct dynamical pathways.  
11                    • The first pathway involves Rossby wave propagation from the North Pacific and  
12                    the cold spell preceding the European windstorm.  
13                    • The second pathway features both extremes occurring roughly at the same time  
14                    thanks to an upper-level anticyclone west of Greenland.

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## Abstract

Winter cold spells over North America have been correlated with European wind extremes, but the physical mechanisms behind such “pan-Atlantic” compound extremes have not been clarified yet. In this study, we propose that pan-Atlantic cold and windy extremes occur following two possible dynamical pathways. The first one involves the propagation of a Rossby wave train from the Pacific Ocean, associated with windstorms over north-western Europe in the 5-10 days after the cold spell peak. The second is associated with a high-latitude anticyclone over the North Atlantic and an equatorward-shifted jet, leading to windstorms over south-western Europe already in the days preceding the cold spell peak. European windstorms are thus consistently tied to North American cold spells according to the different flow configuration. The analysis underscores that seemingly similar surface extremes may be driven by different processes, and that overlooking these subtleties and conflating them together could lead to misleading conclusions.

## Plain Language Summary

Previous research noticed cold spells over North America and windstorms over Europe tend to occur within a few days from each other. This connection is supported by the fact that winds usually blow from west to east over the North Atlantic, embedding with them the cyclones modulating the European weather during winter. However, the chain of processes behind this connection remained not fully clarified. Here we explain the complex relationship between the occurrence of North American cold spells and European windstorms. While previous work tried to identify a single physical mechanism, we suggest that two separate pathways can establish a connection between the two types of extremes. The first pathway resembles the initial hypothesis, as the propagation of a train of cyclones and anticyclones from the North Pacific to the North Atlantic sequentially leads to a North American cold spell and, a few days later, to windstorms over north-western Europe. The second pathway, on the other hand, involves an anomalous anticyclone over the North Atlantic, which acts to induce cold spells over North America and windstorms over south-western Europe roughly at the same time: this still leads to a correlation between the two extremes, but without a clear causality direction.

## 1 Introduction

Cold spells and windstorms are typical examples of cold-season extreme weather events with significant societal and economical impacts (e.g., Karremann et al., 2014; Rytli et al., 2016). The notable winter of 2013/14 featured the co-occurrence of frigid temperatures over North America and of extremely windy and wet conditions over the British Isles, bringing to hypothesize a connection between cold spells over North America and cyclonic activity over western Europe (e.g., Huntingford et al., 2014; Knight et al., 2017). The co-occurrence of cold spells over the United States and of anomalously windy and wet conditions over Europe can be described as a spatially compounding extreme event (Zscheischler et al., 2020), as the two phenomena co-occur over remote regions in a short period of time (Messori et al., 2016; Leeding et al., 2022). The joint occurrence of spatially compounding extremes can magnify their socio-economic impact, exposing actors to correlated losses across their portfolios (e.g., Mills, 2005).

The physical processes behind pan-Atlantic cold and windy extremes likely involves the low-frequency and the transient dynamics of the North Atlantic storm track. Indeed, the continuous generation of cold air over North America during boreal winter modulates the land-sea contrast over the eastern coast of the continent and is a fundamental process for the dynamics of the North Atlantic storm track (Held, 1983; Brayshaw et al., 2009; Portal et al., 2022). However, drivers and possible modulators of this particular type of compound events remain up to now not fully clarified. The work by Messori et al. (2016) selected and composited 60 cold spells over a broad domain in eastern North

65 America with the aim to study how they could affect the North Atlantic storm track and  
66 lead to European wet and windy extremes. Their work highlighted:

- 67 1. An intensification, zonalisation, and equatorward shift of the North Atlantic jet  
68 stream occurring around the time of the cold spell, resulting in overall enhanced  
69 storminess over western Europe.
- 70 2. That North American cold spells are associated with a Rossby wave train arch-  
71 ing from the North Pacific towards Alaska and then the North Atlantic storm track.
- 72 3. Finally, that such an enhancement and equatorward shift of the Atlantic jet stream  
73 emerge as statistically significant already five days before the cold spell peak. The  
74 presence of a significant European impact (in terms of wind extremes) in the 15  
75 days preceding the cold spell was also noticed by Leeding et al. (2022), who thus  
76 hypothesized the presence of a third actor capable of simultaneously driving both  
77 sides of the pan-Atlantic extreme.

78 These results are reminiscent of the pioneering work by Dickson and Namias (1976),  
79 who noticed that periods of lower than usual temperature near the eastern coast of the  
80 United States were associated with enhanced baroclinicity at the entrance of the North  
81 Atlantic storm track. This resulted in extratropical cyclones tracking at lower latitudes  
82 than usual, consistently with an *equatorward-shifted* eddy-driven jet stream. On the other  
83 hand, the propagation of North Pacific wave trains towards the North Atlantic is known  
84 to be associated with a *poleward-shifted* jet stream, projecting approximately onto the  
85 positive phase of the North Atlantic Oscillation (NAO; e.g., Franzke et al., 2004; Bene-  
86 dict et al., 2004; Rivière & Orlandi, 2007; Rivière & Drouard, 2015; Schemm et al., 2018).  
87 The presence of significant jet stream anomalies over the North Atlantic prior to the peak  
88 of the cold spell is also puzzling because, if there indeed was a causal link between cold  
89 spells over North America and downstream storm track anomalies, one would expect the  
90 storm track response to follow the cold spell in time rather than to anticipate it. Dickson  
91 and Namias (1976) can provide a first, plausible hypothesis: they noticed that cold con-  
92 ditions over the eastern coast of North America were tied to the presence of an anticy-  
93 clone over Greenland, in a configuration resembling the negative phase of the NAO. This  
94 potential “upstream” influence of the North Atlantic storm track has been proven to be  
95 particularly important for cold spells in the eastern United States, whose likelihood is  
96 increased during periods of negative NAO (Cellitti et al., 2006; Smith & Sheridan, 2019;  
97 Millin et al., 2022). Based on the literature, we thus hypothesise a complex, two-way in-  
98 teraction between the North Atlantic storm track and North American cold spells, which  
99 offers a possible key to interpret the results of (Messori et al., 2016).

100 This letter aims to elucidate the different drivers of pan-Atlantic cold and windy  
101 compound extremes during boreal winter, reconciling the above open questions with our  
102 current understanding of the dynamics of the North Atlantic storm track. We show that  
103 apparent contradictions likely resulted from the mixing of two different, physically con-  
104 sistent pathways connecting North American cold extremes and European windstorms.  
105 For the sake of conciseness, this work will not focus on the joint occurrence of North Amer-  
106 ican cold spells and European precipitation extremes: however, given that wind and pre-  
107 cipitation extremes often compound due to extratropical cyclones (Owen et al., 2021),  
108 we expect the substance of the results not to change. After an explanation of the em-  
109 ployed data and approach (Sec. 2), the circulation pattern associated with the pan-Atlantic  
110 extremes is revisited for a representative region over central United States (Sec. 3a). Then,  
111 different dynamical pathways associated with the extremes are discussed (Sec. 3b, 3c).  
112 The paper is closed by a contextualization of the results and a summary section (Sec.  
113 4).

## 2 Data and Methods

The analysis is based on ECMWF’s ERA5 Reanalysis data (Hersbach et al., 2020), with a spatial resolution of  $0.5^\circ \times 0.5^\circ$  and a temporal resolution of 1 day between December 1979 and February 2020. Cold spells have been identified following Leeding et al. (2022). They are defined starting from the daily time series of area-averaged 2-meter temperature anomalies during boreal winter (DJF) over  $105^\circ\text{--}85^\circ\text{W}, 35^\circ\text{--}45^\circ\text{N}$ . This region is chosen because it partly overlaps with the one chosen by Messori et al. (2016), but results are rather insensitive to  $5^\circ$  shifts of the domain in the four cardinal directions (not shown). Anomalies are ranked from the absolute largest to smallest and the time of the strongest anomaly (here defined as  $t_{CS}$ ) is retained as the cold spell peak. To ensure independence between events, if two or more cold spell peaks occur within 15 days of each other, only the coldest one is retained. The so-defined 35 coldest days in the region are then used for analysis (see Table S1 in the Supporting Information - SI). For a sensitivity analysis to the exact choice of parameters, we refer to Leeding et al. (2022). European surface wind extremes are defined as exceedances of the 98<sup>th</sup> percentile of 10-meter wind speed for each grid point, with the choice of the percentile threshold following Klawns and Ulbrich (2003). The propagation of low-frequency Rossby wave trains is assessed using the phase-independent formulation of the wave-activity flux (WAF) for stationary, quasi-geostrophic eddies by Takaya and Nakamura (1997). As the resulting wave-activity flux exhibits a significant level of small-scale noise (as noticed also by Wolf & Wirth, 2017), the field was smoothed by retaining only spherical harmonics contributions with  $n < 20$  (see Fig. §1 in the SI). More details about the wave-activity flux computation are provided in the SI.

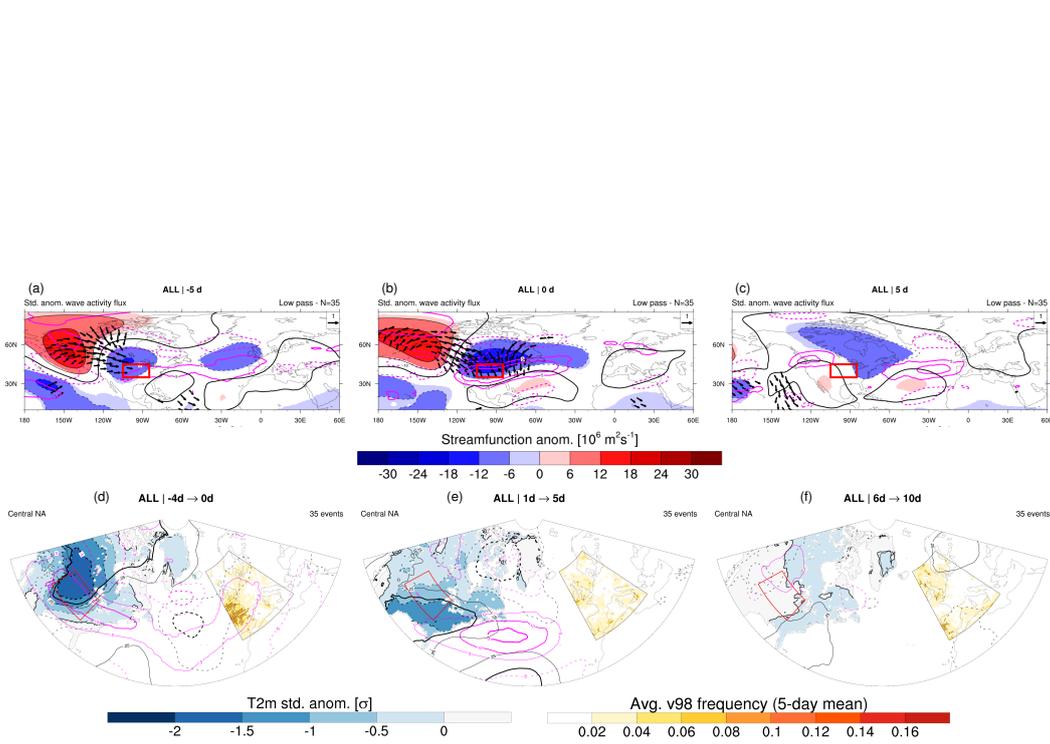
## 3 Results

### 3.1 Revisiting the downstream impact of central NA cold spells

Five days before the peak of the central NA cold spells we analyse here, a Rossby wave train propagates from the North Pacific towards North America (anomalous wave-activity flux arrows in Fig. 1a). The wave train features an enhanced Alaskan ridge and an incipient trough to the South of Hudson Bay: these features are consistent with the known dynamics of cold spells over the region (e.g., Carrera et al., 2004; Palmer, 2014; Xie et al., 2017; Millin et al., 2022). A second trough, seemingly unrelated to the North Pacific wave train, is visible west of Europe. This negative streamfunction anomaly is associated with strong upper-level winds at its southern flank, resulting in a significantly enhanced occurrence of extreme surface winds over the Iberian Peninsula and France in the days preceding the cold spell (Fig. 1d).

As the cold spell reaches its peak ( $t_{CS}$ ) and the Rossby wave train propagates towards the Atlantic, the upper-level jet stream intensifies at the southern edge of the trough over North America and extends eastward (Fig. 1b). Meanwhile, the previously described trough west of Europe merges with the larger one over North America and presumably contributes to the maintenance of an equatorward-shifted jet stream, although significant surface wind extremes are no longer visible over Iberia (Fig. 1e). The propagation of the wave train appears to influence the position and the tilt of the waveguide at the North Atlantic storm track entrance (maximum zonal wind anomaly of  $15 \text{ m s}^{-1}$ , Fig. 1b). The upper-level jet is confined between the trough over North America, directly associated with the cold spell, and the anticyclone located in the subtropics, located at the leading edge of the wave train.

After the cold spell, the trough-ridge system associated with the Rossby wave train continues to shape the North Atlantic waveguide, featuring an enhanced gradient of geostrophic streamfunction and an anomalously strong upper-level jet stream directed towards western Europe (Fig. 1c). This is associated with significant extreme surface wind anoma-



**Figure 1.** (Top) Lagged composites of 250 hPa wave-activity flux standardized anomalies (arrows), geostrophic streamfunction anomalies (black contours, shaded significant values) and zonal wind anomalies (magenta contours, only  $\pm 5 \text{ m s}^{-1}$ ,  $\pm 10 \text{ m s}^{-1}$ , negative values dashed) for the 35 cold spells occurring over the considered central NA region ( $105^\circ\text{--}85^\circ\text{W}$ ,  $35^\circ\text{--}45^\circ\text{N}$ ) for (a)  $t_{CS} - 5$  d (b)  $t_{CS}$ , (c)  $t_{CS} + 5$  d. Vectors are shown, and streamfunction anomalies are shaded, only when exceeding the top 99% or bottom 1% of a 2500-times randomly sampled distribution. (Bottom) Composites of extreme (above 98th percentile) 10m wind frequency over Europe, averaged over 5 days, and of standardized 2-meter temperature anomaly over North America and Greenland (notice the two separate color scales) for 5-day periods centered at (d)  $t_{CS} - 2$  d, (e)  $t_{CS} + 3$  d, (f)  $t_{CS} + 8$  d. Overlaid are composites of 250 hPa wind anomaly (magenta contours, only  $\pm 5 \text{ m s}^{-1}$ ,  $\pm 10 \text{ m s}^{-1}$ ,  $\pm 15 \text{ m s}^{-1}$ ), sea level pressure standardized anomaly (black contours, only  $\pm 0.25 \sigma$ ,  $\pm 0.5 \sigma$ ), with negative values dashed. Stippling indicates significantly heightened frequency of extreme 5-day-averaged 10m wind with respect to the top 99% or bottom 1% of a 10000-times randomly sampled distribution.

164 lies over both the British Isles and the Iberian Peninsula (Fig. 1f; see also e.g., Gómara  
 165 et al., 2014; Messori & Caballero, 2015; Messori et al., 2016). The large-scale configu-  
 166 ration projects onto a significantly negative NAO phase in the days preceding the cold  
 167 spell, but it moves towards more neutral to positive conditions as the cold spell unfolds  
 168 (Fig. S2a). The anomalous configuration of the upper-level jet stream is also visible us-  
 169 ing classical jet indices, which indicate a stronger, more equatorward-displaced and zonal  
 170 jet than usual (as in Figs. Sb-d in the Supplementary Information). The separate trough  
 171 over western Europe is no longer visible.

172 In summary, the composites show a wave train upstream of the North American  
 173 cold spell and the elongation of the North Atlantic jet stream towards western Europe  
 174 already in the days preceding the cold spell peak, as previously highlighted by Messori  
 175 et al. (2016). Such a significant anomaly indicates a potential role of North Atlantic storm  
 176 track dynamics for the genesis of the cold spells; this would however be in apparent con-  
 177 trast, with the role of the North Pacific Rossby wave train as driver of the cold spells,  
 178 discussed by previous literature.

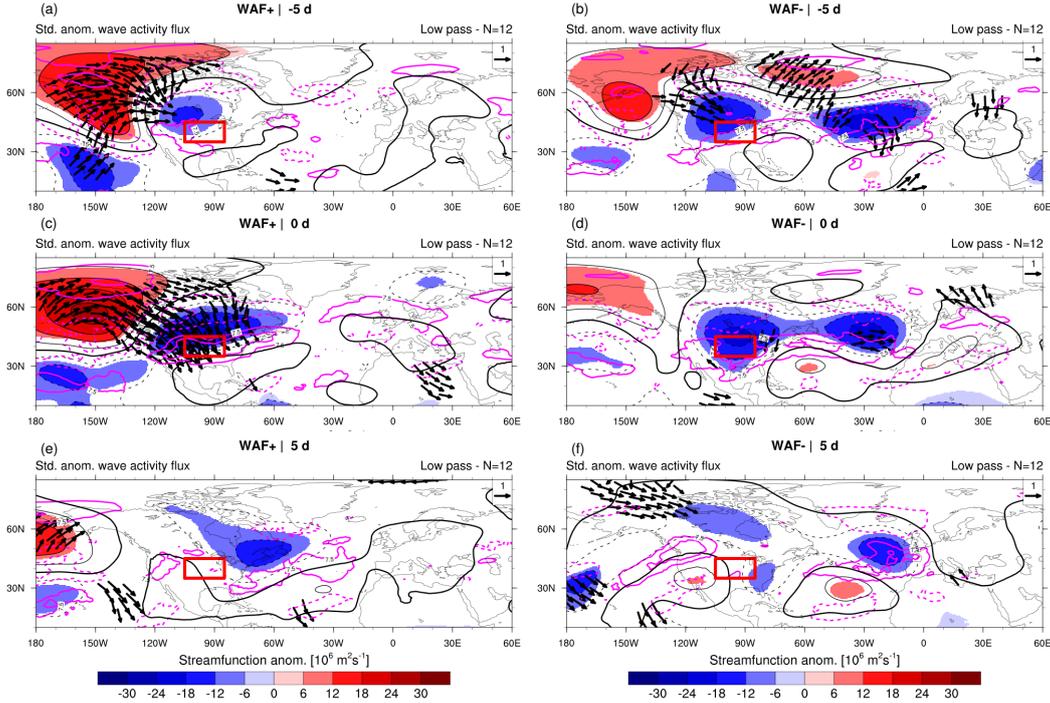
### 179 3.2 Stratification with respect to wave-activity flux

180 The considerations above suggest a need to compare the relative importance of North  
 181 Pacific wave trains with respect to the dynamics of the North Atlantic storm track dur-  
 182 ing the cold spells. To verify this, we compute the area-averaged magnitude of the wave-  
 183 activity flux anomaly vector  $|\text{WAF}_{\text{anom}}|$  over the considered region ( $105^\circ\text{-}85^\circ\text{W}$ ,  $35^\circ\text{-}45^\circ\text{N}$ )  
 184 and stratify the same set of cold spells with respect to  $|\text{WAF}_{\text{anom}}|$  at cold spell peak. The  
 185 metric is averaged over the considered cold spell domain, under the assumption that lo-  
 186 cal anomalies in wave-activity flux are indicative of the strength of Rossby wave prop-  
 187 agation during the cold spell. We then extract the 12 cold spells associated, respectively,  
 188 with the top (WAF+) and bottom (WAF-) terciles of  $|\text{WAF}_{\text{anom}}|$  and discuss their dif-  
 189 ferences.

190 A composite analysis shows that cases in the WAF+ subset are indeed character-  
 191 ized by the clear propagation of a Rossby wave train from the North Pacific as the cold  
 192 spell develops and peaks (Figs. 2a,c). Anomalies in geostrophic streamfunction and wave-  
 193 activity flux over the north-western portion of North America appear to precede the cold  
 194 spell also for cases in the WAF- subset, although with a weaker signal than for the WAF+  
 195 case (Fig. 2b). The two cold spell subsets are also associated with significantly different  
 196 flow configurations over the North Atlantic, especially in the days preceding the cold spell  
 197 (Fig. 2a,b). For WAF+, no significant streamfunction anomalies are visible over the North  
 198 Atlantic before or during the cold spell peak (Figs. 2a,c). As the wave train propagates  
 199 over the North Atlantic, the jet tilts poleward over the eastern Atlantic in the direction  
 200 of the British Isles (Fig. 2e).

201 The situation is radically different for the WAF- subset. First of all, an anomalous  
 202 flow pattern resembling a negative NAO phase is visible over the North Atlantic in the  
 203 days before the cold spell, with an upper-level high over Greenland and two troughs at  
 204 its southern flanks: one over eastern North America and one over western Europe. Be-  
 205 low these, an equatorward-shifted jet is found (Fig. 2b). The unfolding of the WAF- cold  
 206 spells does not substantially alter the flow configuration over the North Atlantic: the jet  
 207 remains anomalously equatorward-shifted, and two separate troughs are still visible over  
 208 the western and eastern parts of the North Atlantic basin (Figs. 2d,f). In this scenario  
 209 there is no strict need of a precursor North Pacific Rossby wave train: however, the pres-  
 210 ence of a weak but significant Alaskan ridge in the WAF- composite (Figs. 2b,d) suggests  
 211 that this feature can still be relevant for particularly intense and/or persistent cold spells.

212 This analysis explains why central NA cold spells are not followed by a systemat-  
 213 ically positive or negative NAO (Fig. §3a), as the state of the North Atlantic storm track  
 214 is conditioned by which dynamical pathway the cold spell is associated with. More pro-

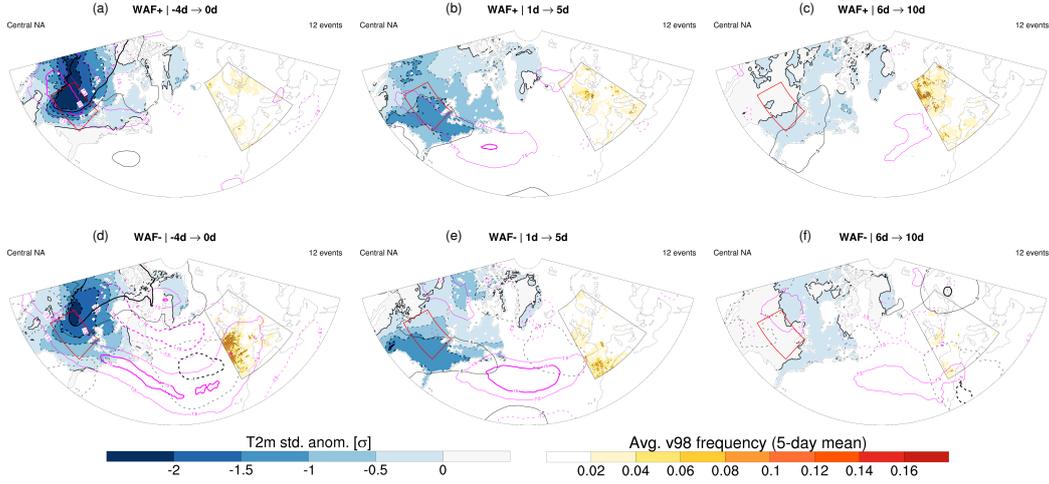


**Figure 2.** Lagged composites of standardized WAF anomalies (arrows), geostrophic streamfunction anomalies (shaded) and 250 hPa zonal wind anomalies (magenta contours, only  $\pm 7.5 \text{ m s}^{-1}$ ,  $\pm 15 \text{ m s}^{-1}$ , negative values dashed) for the 12 central NA cold spells in the (left) WAF+ and (right) WAF- subsets at lags (a,d)  $t_{CS}-5 \text{ d}$  (b,e)  $t_{CS}$ , and (c,f)  $t_{CS}+5 \text{ d}$ . Only significant WAF vectors and streamfunction anomalies are shown (with respect to the top 99% or bottom 1% of a 10,000-times randomly sampled distribution).

215 pronounced differences between WAF+ and WAF- emerge when looking at jet speed and  
 216 latitude, while jet zonality is not systematically different (Figs. §3b-d). As a backward  
 217 check, we also note that these two distinct dynamical pathways can be re-obtained from  
 218 a stratification based on the upper and lower terciles of the NAO index four days *after*  
 219 cold spell peak (see Fig. S4 in the SI). The corresponding 12-cold spell subsets are named  
 220 NAO+ and NAO-, respectively. The NAO+ cold spells correspond to the NW-SE prop-  
 221 agation of a Rossby wave train across North America (Figs. S4a,c), resulting in an en-  
 222 hanced jet stream over the North Atlantic. On the other hand, the NAO- cold spells fea-  
 223 ture an upper-level anticyclone west of Greenland and an equatorward-shifted jet stream  
 224 over the Iberian Peninsula already four days before the cold spell peak (Fig. S4b), a sit-  
 225 uation that remains virtually unchanged as the cold spell unfolds (Figs. S4d,f).

### 226 3.3 Implications for surface extremes

227 The two different dynamical pathways associated with the cold spells are mirrored  
 228 in differences in the occurrence of European surface wind extremes. In the WAF+ sub-  
 229 set, no extreme winds are observed over western Europe preceding the cold spell peak  
 230 (Figs. 3a,b). This is in sharp contrast with the image gained from the whole subset of  
 231 the 35 cold spells, which featured a significantly heightened frequency of extreme winds  
 232 over the Iberian Peninsula and France preceding the cold spell peak (cf. Fig. 1d). On the  
 233 other hand, the WAF- cold spell subset displays extreme surface winds accompanied by  
 234 lower than usual sea-level pressure over the Azores and upper-level wind anomalies ex-  
 235 tending through the whole North Atlantic basin prior to the cold spell peak (Fig. 3d).



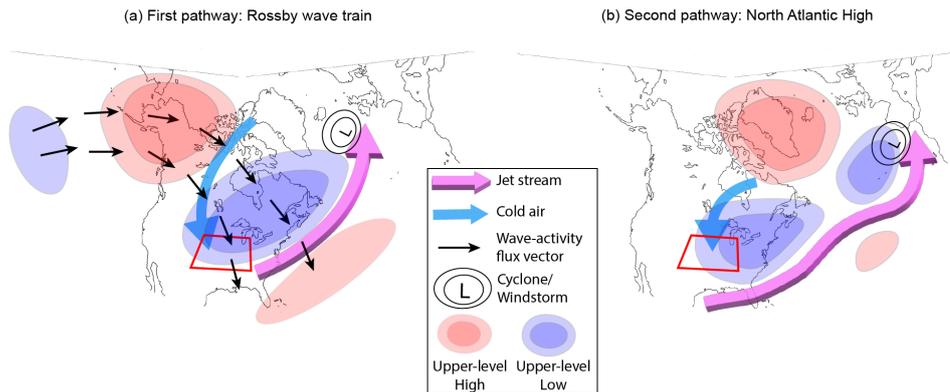
**Figure 3.** Composites of extreme (above 98th percentile) 10m wind frequency over Europe, averaged over 5 days, and of standardized 2-meter temperature anomaly over North America and Greenland (notice the two separate color scales) following cold spells over central NA belonging to the (top) WAF+ and (bottom) WAF- subsets for the 5-day periods centered at (a,d)  $t_{CS}-2d$ , (b,e)  $t_{CS}+3d$ , (c,f)  $t_{CS}+8d$ . Overlaid are composites of 250 hPa wind anomaly (magenta contours, only  $\pm 7.5 \text{ m s}^{-1}$ ,  $\pm 15 \text{ m s}^{-1}$ ), sea level pressure standardized anomaly (black contours, only  $\pm 0.25 \sigma$ ,  $\pm 0.5 \sigma$ ), with negative values dashed. Stippling indicates 5-day-averaged frequencies of extreme 10m wind exceeding the top 99% or bottom 1% of a randomly sampled distribution.

236 Indeed, extreme surface winds occur mostly in the period preceding, rather than follow-  
 237 ing, the cold spell peak (Figs. 3e,f). The WAF- subset thus appears characterized by *con-*  
 238 *current* developing cold spells over central NA and extreme surface winds over western  
 239 Europe. This co-occurrence is likely related to the two troughs visible at the entrance  
 240 and the exit of the North Atlantic storm track (Figs. 2d,f): while the trough to the west  
 241 advects cold air at its western flank towards the central NA region, the trough to the east  
 242 is tied to an upper-level jet streak at its southern flank, associated with extreme winds  
 243 over the Iberian Peninsula (Figs. 3d,e). In addition, the dynamics portrayed in the WAF-  
 244 subset are consistent with the streamfunction and jet anomalies visible in the full com-  
 245 posite (Fig. 1). We thus hypothesize that the puzzling European wind extremes observed  
 246 *before* the cold spell peak are mostly related to this second pathway for pan-Atlantic cold  
 247 and windy extremes, in which the North Atlantic storm track is already in a state con-  
 248 ductive to European wind extremes before the cold spell peak is reached over Central NA.  
 249 Given that the Greenland high is likely emerging from the activity of the North Atlantic  
 250 storm track, it makes sense that its impacts are felt over Europe first (i.e., in term of wind-  
 251 storms), and then upstream over North America (i.e., in terms of large-scale setup lead-  
 252 ing to cold spells). This mechanism would explain the anticipated wind impact of cen-  
 253 tral NA cold spells noticed by Messori et al. (2016) and Leeding et al. (2022).

## 254 4 Concluding remarks

### 255 4.1 Summary

256 Cold spells over central NA are impactful weather events whose occurrence has been  
 257 empirically related to windstorms over Europe. The underlying hypothesis was that Eu-  
 258 ropean windstorms were occurring as a “downstream response” of the “upstream” cold  
 259 spells. The results of this study challenge this view and allow us to conclude that there



**Figure 4.** Schematic of the two pathways connecting North American cold spells and European windstorms. (a) In the first pathway, the various upper-level anomalies are related to the propagation of a Rossby wave train from the North Pacific, indicated by the series of thin, black arrows connecting the ridge over Alaska with the trough over eastern North America. (b) In the second pathway, the jet stream is located more equatorward than usual and is associated with anomalous cyclonic activity over south-western Europe.

260 are at least two possible dynamical pathways to explain the observed statistical link be-  
 261 tween North American cold spells and European windstorms:

- 262 1. Cold spells characterized by the presence of a ridge over Alaska, which is part of  
 263 a eastward-propagating, low-frequency Rossby wave train, are not associated with  
 264 significant anomalies over the North Atlantic before cold spell peak. The effect  
 265 over the North Atlantic storm track manifests itself only when the wave train  
 266 reaches the eastern portion of the continent, resulting in a tilted, intensified jet stream  
 267 and in wind extremes over north-western Europe in the 6-10 days following cold spell  
 268 peak. In this pathway, the propagation of the wave train supports a clear causal  
 269 link between the circulation pattern causing the cold spell (the Rossby wave train),  
 270 its impact onto the storm track and the surface wind extremes over Europe (Fig. 4a).
- 271 2. The presence of a high west of Greenland is associated with a flow configuration  
 272 that promotes the development of cold spells over North America and windstorms  
 273 over Europe at the same time. In particular, the high is often related to the south-  
 274 ward displacement of a trough over the eastern United States, which promotes cold  
 275 air advection at its western flank. At the same time, the large-scale configuration  
 276 is related to an equatorward shift of the upper-level trough normally associated  
 277 with the Icelandic Low: this configuration resembles a negative NAO pattern, con-  
 278 ductive to extreme winds over south-western Europe (Fig. 4b). As the two weather  
 279 extremes *co-occur* in time and are associated with a common precursor (the afore-  
 280 mentioned Greenland high), it would then be inappropriate to discuss European  
 281 windstorms as a “downstream effect” of North American cold spells.

282 In summary, the different drivers of central NA cold spells correspond to different  
 283 circulation patterns over the North Atlantic, which are then related to an increased fre-  
 284 quency of windstorms over different European regions in a physically consistent man-  
 285 ner. In the specific case discussed in this study, the original composite picture retained  
 286 characteristics of the two different drivers at the same time lags, leading to a nonphys-  
 287 ical large-scale configuration where the European wind extremes appear to precede the  
 288 North American cold spell that should cause them. Thus, analyzing pan-Atlantic cold  
 289 and windy extremes without considering their dynamical drivers can lead to an incom-

plete, or at worst incorrect, understanding of their dynamics. A similar cautionary argument likely applies to studies concerning temporally and spatially compounding extremes over remote regions (e.g., summer heatwaves or winter cold spells).

## 4.2 Contextualization of the results and outlook

The two distinct pathways connecting central NA cold spells and European windstorms were identified by stratifying with respect to the area-averaged WAF over the selected cold spell region. Two cold spell subsets were then obtained by selecting the dates corresponding to values in the upper or lower WAF terciles, respectively. Other possible ways to perform this division were attempted, for instance by considering area-averaged wave-activity flux over Alaska, but this choice did not yield a clear division (mainly because not all waves propagating from Alaska engender a cold spell in a given North American region). We thus regard our chosen partition as a simple and physically-grounded way to unravel the different dynamical pathways behind temporally compounding pan-Atlantic cold and windy extremes.

This work focused on a single yet representative North American cold spell domain, but the relative weight of the two pathways likely differs for different regions. Future work will involve a more comprehensive analysis trying to identify differences in the physical connections to European windstorms for cold spells in different North American regions. Another caveat of this analysis is the reduced number of extreme cold spells considered (a total of 35, with 12 cases in the WAF+ and WAF- subsets). We nonetheless underscore the high level of statistical significance of our results. Furthermore, we did not analyse possible remote drivers behind the two identified pathways. Possible candidates are tropical convection anomalies over SE Asia and the maritime continent, which have been linked to the forcing of Rossby wave trains over the Pacific Ocean (e.g., Teng & Branstator, 2017; Riboldi et al., 2022), or the occurrence of sudden stratospheric warmings, which have been connected with the formation of high-latitude anticyclones and with an equatorward displacement of the jet stream over the North Atlantic basin (e.g., Kolstad et al., 2022).

The chosen central NA region is located roughly in the middle between the Pacific and the Atlantic Oceans, and the two identified pathways for pan-Atlantic cold and windy extremes reflect the role played by the basins. The first pathway features a strong wave propagation from the upstream North Pacific, while the second one appears more influenced by high-latitude upper-level ridges over Greenland and the Canadian Arctic, that plausibly result from the dynamics of the North Atlantic storm track (e.g., atmospheric blocking following explosive cyclogenesis). This indicates that both basins can play a role in the genesis of central NA cold spells, as hinted by Lee et al. (2019) and recently emphasized by Millin et al. (2022) using a weather regime approach. This conceptualization has now been extended to the North Atlantic basin, so that pan-Atlantic wet and windy extremes can be seamlessly understood as part of individual large-scale flow configurations tied to the activity of the Pacific and Atlantic storm tracks. In conclusion, this study provided an interesting case-study of the role played by hemispheric-scale teleconnections in coordinating extreme weather events across North America and Europe, paving the way to frameworks for the prediction and mitigation of their joint impacts.

## 5 Open Research

ERA5 hourly data from 1979-present are available for several pressure levels (Hersbach et al., 2018a) and for surface variables (Hersbach et al., 2018b). Both data sets were freely downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store.

## Acknowledgments

JR, RL and GM acknowledge funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement no. 948309, CENÆ project). The authors also wish to thank Paolo Ghinassi for the helpful discussions about properties of the wave-activity flux.

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