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# **Diagnosing the Systematic Occurrence of Wintertime Compound Climate Extremes in North America and Europe**

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## **Key Points:**

- North American cold spells and European wet or windy extremes are very strongly coupled to recurrent large-scale atmospheric patterns.
- Compound cold–wet–windy anomalies in North America and Europe are closely connected and share common atmospheric circulation patterns.
- Compound cold–wet–windy extremes show a weaker connection than the anomalies, but are nonetheless linked.

20 **Abstract**

21 The repeated co-occurrence of cold spells over Eastern North America and wet or windy  
22 extremes over Western Continental Europe during recent winters, has led to hypothesise a link  
23 between the two. Here, we provide a systematic analysis of the interplay between the large-scale  
24 atmospheric circulation and co-occurring cold spells in North America and wet or windy  
25 extremes in Europe, which we collectively term compound cold–wet–windy extremes. We  
26 leverage a recent approach grounded in dynamical systems theory, which provides an  
27 analytically and computationally efficient analysis of spatially resolved, multivariate climate  
28 extremes. We find that there are specific, recurrent large-scale atmospheric circulation patterns  
29 systematically associated with co-occurring cold–wet–windy anomalies. Evidence for this is also  
30 found when focussing on compound cold–wet–windy extremes, although with a weaker signal.  
31 This motivates further analyses focussing specifically on the statistics and drivers of the  
32 compound extreme occurrences.

33 **Plain Language Summary**

34 In recent winters, very cold weather over the eastern part of North America and stormy weather  
35 or heavy rainfall in Europe have often made the news. One may think that these events are  
36 independent, since they occur several thousands of kilometres apart. However, researchers have  
37 hypothesised that there may be weather patterns that connect these different weather episodes.  
38 Here we test this idea. We find that there is indeed a connection between unusually cold weather  
39 in Eastern North America and unusually stormy weather and heavy rainfall in Western  
40 Continental Europe. We also find a link, albeit weaker, when focussing specifically on extreme  
41 events – namely only the coldest of the cold spells, the windiest of the storm days and the wettest  
42 of the heavy rainfall days. The strongest connection, however, emerges when looking at unusual  
43 but not extreme weather episodes.

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## 52 **1 Introduction**

53 During recent winters, ostensibly frequent cold spells in Eastern North America and wet or  
54 windy extremes in Western Continental Europe have garnered widespread scientific attention  
55 (e.g. Palmer 2014; Lee et al., 2015; Matthias and Kretschmer, 2020; van Oldenborgh et al., 2015;  
56 Hillier and Dixon, 2020; Owen et al., 2021). The two event classes have typically been discussed  
57 separately. However, their repeated co-occurrence has led to hypothesise that these are spatially  
58 compounding extremes, namely extremes that occur at geographically remote locations but are  
59 associated with common physical drivers. Specifically, Messori et al. (2016) argued for a link  
60 mediated by large-scale atmospheric circulation anomalies over the North Atlantic. They  
61 conditioned their analysis on Eastern North American cold spells, finding that these matched  
62 positive precipitation and wind anomalies over parts of Europe. However, extreme wet or windy  
63 weather in Europe was not investigated. A later study by De Luca et al. (2020) focussed on co-  
64 occurring cold extremes in North America and wet extremes in Europe, providing partial support  
65 for the hypothesis of Messori et al. (2016). The study used an approach similar to the one we will  
66 adopt here, yet did not consider variables associated with the large-scale atmospheric circulation  
67 nor wind extremes in Europe. The current understanding of co-occurring cold spells in North  
68 America and wet or windy extremes in Europe, which we collectively term compound cold–wet–  
69 windy extremes, is thus incomplete. Filling this knowledge gap is all the more urgent in view of  
70 the growing awareness of the relevance of compound extremes, whose impacts often exceed the  
71 sum of those due to the individual events comprising them (Zscheischler et al., 2018).

72 The multivariate perspective inherent to compound extremes, adds complexity to conventional  
73 statistical tools for the study of extremes (Naveau, 2005). A wide range of approaches have been  
74 proposed to deal with multivariate extreme value statistics in climate data, from copula-based  
75 methods to max-stable models, conditional exceedance models, machine learning algorithms and  
76 more (e.g. Oesting and Stein, 2018; Brunner et al., 2019; Tavakol et al., 2020; Towler et al.,  
77 2020; Vogel et al., 2021). Spatially compounding extremes, such as the ones we consider here,  
78 present the additional challenge of how to incorporate spatial information in the analysis. Some  
79 of the above multivariate statistical approaches may be extended to incorporate spatial  
80 information, but this often results in highly complex models (e.g. Genton, 2015; Liu et al., 2021).

81 Here, we leverage dynamical systems theory to provide an analytically and computationally  
82 efficient, spatially resolved analysis of compound cold–wet–windy extremes in North America  
83 and Europe. The approach builds upon recent advances in dynamical systems theory (Faranda et  
84 al., 2020a), and allows to compute a metric reflecting the instantaneous coupling between  
85 different atmospheric variables, which we term co-recurrence ratio, or  $\alpha$ . In this study, we extend  
86 this approach for the first time beyond the bivariate case. We propose this as an effective  
87 complement to existing analyses of spatially compounding extremes, which may support our  
88 understanding of the interplay between different climate extremes and their physical drivers.

89 Motivated by the incomplete knowledge on compound cold–wet–windy extremes in North  
90 America and Europe, we specifically seek to answer the following questions:

91 (i) Do cold spells over Eastern North America and wet or windy extremes over Western  
92 Continental Europe individually emerge as events with a particularly strong coupling to large-  
93 scale circulation patterns?

94 (ii) Is there evidence for recurrent large-scale circulation patterns systematically associated with  
95 the co-occurrence of these extremes?

96 Concerning the first question, there is a vast literature dealing with large-scale circulation  
97 patterns favouring the extremes analysed here (e.g. Haylock and Goodess, 2004; Cellitti et al.,  
98 2006; Donat et al., 2010; Grotjahn et al., 2015; Harnik et al., 2016; Smith and Sheridan, 2018;  
99 Laurila et al., 2021). However, the question of whether the coupling of these extremes with the  
100 large-scale circulation is unusually strong relative to other days has not been addressed (with the  
101 exception of an exploratory analysis for North America in Faranda et al., 2020a). Concerning the  
102 second question, Messori et al. (2016) conditioned their large-scale atmospheric analysis only on  
103 cold spells in Eastern North America, without accounting for European extremes. We begin by  
104 analysing separately North America and Europe, and then consider a multivariate analysis  
105 explicitly addressing the spatially compounding nature of the cold–wet–windy extremes.

## 106 **2 Data**

107 We use ECMWF’s ERA5 reanalysis data, over boreal winter (December–January–February,  
108 DJF) 1979–2020 and with a horizontal resolution of  $0.5^\circ$  (Hersbach *et al.*, 2020). We compute

109 daily averages from hourly data for surface variables and 6-hourly data for pressure-level  
110 variables. Anomalies are defined relative to a smoothed daily climatology (using a 15-day  
111 running mean, similar to Harnik *et al.*, 2016). Extreme events are diagnosed using anomalies of  
112 2-metre temperature (t2m), 10-metre wind (10m wind) and total precipitation (tp). Large-scale  
113 atmospheric patterns are diagnosed using sea-level pressure (SLP). We chose this over  
114 geopotential height, as the latter displays long-term trends that could affect our dynamical  
115 systems analysis (Faranda *et al.*, 2020b).

116 The t2m in North America is analysed over 30–45 °N 260–290 °E (grey box in Fig. 1a), while  
117 10-m wind and precipitation in Europe are analysed over 45–60 °N 350–20 °E (grey box in Fig.  
118 2a). These domains approximately follow those used in Messori *et al.* (2016) for Eastern North  
119 American cold spells and the area of high windstorm occurrence in Western Continental Europe  
120 identified in Hanley and Caballero (2012), respectively. The same domains are also used for  
121 analysing SLP co-recurrences (see Sect. 3). A sensitivity analysis using larger domains is  
122 presented in the Supplementary Material. To avoid double-counting cold spells, we impose a  
123 minimum separation of 5 days between successive events, following Messori *et al.* (2022). A  
124 similar minimum separation is imposed when selecting high  $\alpha$  days and when selecting single-  
125 gridbox extremes. Unless otherwise specified, all figures are computed for the 50 most extreme  
126 events.

127 Unless otherwise specified, we test statistical significance of composites by verifying whether at  
128 least 2/3 of composite members have the same sign. This provides an indication of the coherence  
129 of the signal across composite members. Assuming a binomial formula with equal chances for  
130 positive and negative anomalies, the probability of obtaining a greater than 2/3 sign agreement  
131 randomly is well below 5%.

132

### 133 **3 Diagnosing the Coupling of Atmospheric Variables**

134 Our analysis rests on an indicator of the instantaneous coupling of multiple atmospheric  
135 variables, termed *co-recurrence ratio*, or  $\alpha$  (Faranda *et al.*, 2020a; see also applications in De  
136 Luca *et al.*, 2020a,b and Messori and Faranda, 2021). Given two variables drawn from a chaotic  
137 dynamical system,  $\alpha$  measures the extent to which recurrences in one variable correspond to  
138 recurrences in the other. For example,  $\alpha$  computed for SLP and t2m over a given geographical

139 domain, diagnoses how often, given the recurrence of a specific t2m spatial pattern in the  
140 domain, one also observes the recurrence of the associated SLP spatial pattern. In other words, if  
141  $\alpha$  at a given timestep  $t$  in our dataset is large, then every time a t2m pattern similar to the t2m  
142 pattern of time  $t$  appears in the dataset (a *recurrence*), then the SLP pattern at that other time will  
143 also resemble the SLP pattern of time  $t$ . This may then be interpreted as a high coupling. The  
144 converse holds for low  $\alpha$ . The co-recurrence ratio may also be computed for more than two  
145 variables. In this case, it diagnoses the extent to which one observes simultaneous recurrences of  
146 all the variables being considered. When computing  $\alpha$  for more than two variables, one is thus  
147 imposing additional constraints relative to the bivariate case. We therefore expect a trivariate  $\alpha$  to  
148 display lower values than its bivariate counterpart.

149 Unlike other statistical coupling measures,  $\alpha$  is instantaneous in time (local in phase space). This  
150 implies that a value of  $\alpha$  is obtained for each timestep in the dataset being analysed. Since  $\alpha$  is  
151 independent of the ordering of the variables, it may not be interpreted in terms of causality. The  
152 range of the co-recurrence ratio is  $0 \leq \alpha \leq 1$ . We provide the details of the calculation of  $\alpha$  for  
153 climate data in Text S1.

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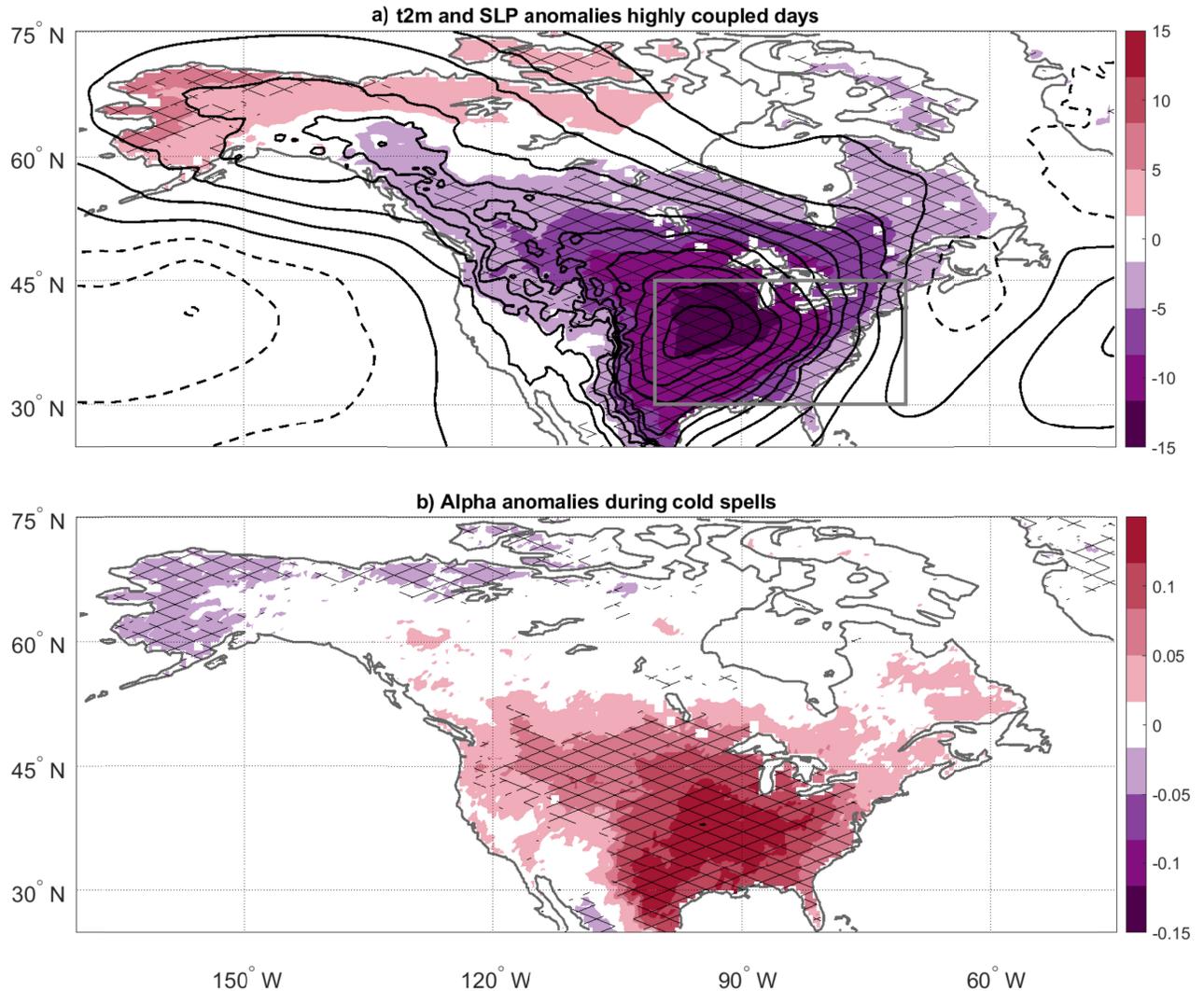
## 155 **4 Large-scale drivers of cold spells in Eastern North America and wet or windy extremes in** 156 **Western Continental Europe**

### 157 **4.1 An Analysis of Individual Extreme Event Classes**

158 We first study separately cold spells in Eastern North America and wet or windy extremes in  
159 Western Continental Europe. To verify how these extremes couple to large-scale atmospheric  
160 patterns, we compute  $\alpha$  between the relevant impact variable and SLP (see Sect. 2). We begin by  
161 analysing days on which t2m in North America is highly coupled to SLP. The 50 days with the  
162 highest coupling display an anomalous high pressure centred to the south-west of the Great  
163 Lakes region, flanked by two negative pressure anomaly cores (Fig. 1a; *cf.* Faranda *et al.*,  
164 2020a). This tripole favours oceanic airmass advection and warm anomalies over Alaska, and at  
165 the same time northerly advection of cold high-latitude air further to the east. Anomalies in  
166 excess of -10 K are attained over the eastern part of the continent, even though we are  
167 conditioning solely on  $\alpha$ . The large-scale pattern is remarkably similar to that obtained by  
168 conditioning on the 50 coldest spells in Eastern North America (Fig. S1a), and resembles the  
169 spatial patterns found by previous studies investigating North American cold spells (*e.g.* Cellitti

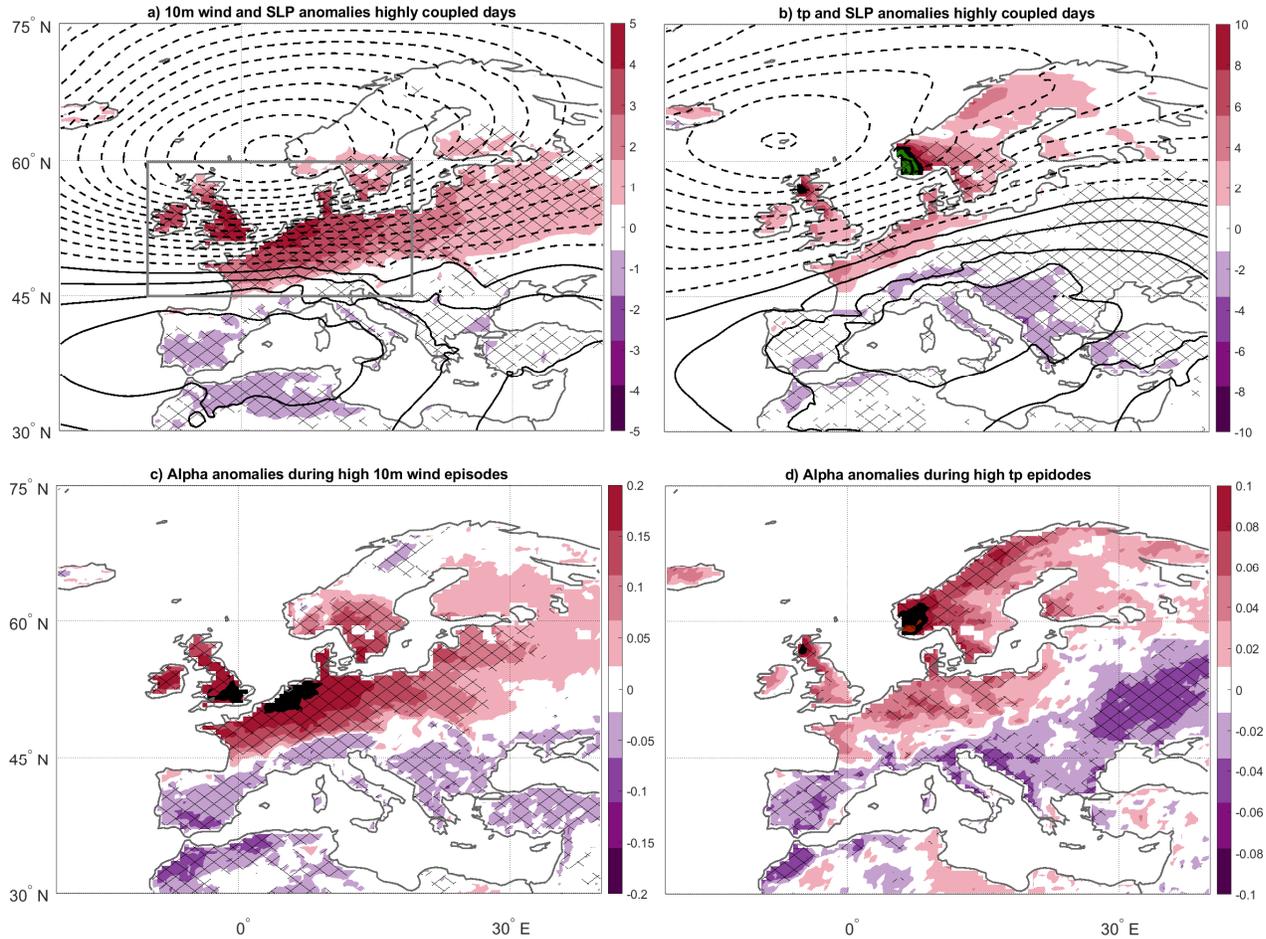
170 *et al.*, 2006; Messori *et al.*, 2016; Harnik *et al.*, 2016; Smith and Sheridan, 2018). Additionally,  
171 the 50 days with the highest coupling between SLP and t2m show an anomalously frequent  
172 occurrence of cold spells over a broad swath of North America (Fig. S2a). Finally, we compute  
173 the  $\alpha_{t2m,SLP}$  anomalies associated with the 50 coldest spells defined at each individual gridbox  
174 (Fig. 1b). The region that shows negative temperature anomalies in Figs. 1a, S1a also displays  
175 positive  $\alpha_{t2m,SLP}$  anomalies in Fig. 1b. Thus,  $\alpha$  shows that the cold spells share a similar spatial  
176 footprint and are systematically associated with a recurrent SLP configuration. We conclude that  
177 the occurrence of cold spells in Eastern North America is systematically associated with a  
178 stronger than usual coupling between SLP and t2m. The qualitative results are not dependent on  
179 the choice of computing  $\alpha_{t2m,SLP}$  by using the same geographical domain for both variables.  
180 Indeed, if we compute  $\alpha_{t2m,SLP}$  using t2m over the cold spell box and the SLP pattern over a much  
181 larger North American domain, the results are qualitatively comparable (Fig. S3).

182 We next shift the focus to 10m wind and tp anomalies in Europe. The 50 days with the highest  
183 coupling between 10m wind and SLP display strong positive 10m wind anomalies over Western  
184 Continental Europe and an SLP anomaly dipole with a strong negative core to the south-east of  
185 Iceland and a weaker positive core over the western Mediterranean (Fig. 2a). This eastward-  
186 shifted, NAO-like dipole is typically associated with a zonalised and intensified jet stream,  
187 which in turn results in heightened cyclone frequency and wind destructiveness over Western  
188 Europe (Donat *et al.*, 2010; Hanley and Caballero, 2012; Gómara *et al.*, 2014; Messori and  
189 Caballero 2015; Messori *et al.*, 2019). A similar SLP anomaly pattern, albeit with a northward-  
190 eastward shifted positive SLP core, is found for the 50 days with the highest coupling between tp  
191 and SLP (Fig. 2b). Because of the shift in the SLP core, the positive tp anomalies are also shifted  
192 slightly northwards relative to the 10m wind anomalies. We reconduct the geographical overlap  
193 between the 10m wind and tp anomalies to the dominant role of North Atlantic extratropical  
194 cyclones in bringing both strong winds and heavy precipitation to Western Europe, which in turn  
195 results in a close relationship between these two classes of extremes (De Luca *et al.*, 2020a;  
196 Owen *et al.*, 2021). This relationship emerges here in the form of a high coupling between SLP  
197 patterns favouring the presence of cyclones over the continent (see references above) and large  
198 10m wind and tp anomalies there. These SLP, tp and 10m wind anomaly patterns are  
199 additionally very similar to those conditioned on the occurrence of tp or 10m wind extremes in  
200 the region of interest (Fig. S1b, c).



201

202 **Figure 1.** Cold spells and high t2m–SLP coupling days in North America. (a) t2m (K, colours)  
 203 and SLP (hPa, contours) anomalies for the 50 days displaying the highest  $\alpha_{t2m,SLP}$ . (b) Anomalies  
 204 in  $\alpha_{t2m,SLP}$  observed during the 50 coldest spells at each gridbox. SLP contours in (a) are every 2  
 205 hPa (negative dashed). Cross-hatching marks regions where at least two thirds of the (a) t2m and  
 206 (c)  $\alpha_{t2m,SLP}$  anomalies share the same sign. All  $\alpha$  are computed over 30–45 °N 260–290 °E (grey  
 207 box in (a)).  
 208



209

210 **Figure 2.** Extremes in 10m wind and tp and days with high 10m wind or tp coupling with SLP in  
 211 Europe. (a) 10m wind ( $\text{m s}^{-1}$ , colours) and SLP (hPa, contours) anomalies during the 50 days  
 212 displaying the highest  $\alpha_{10m\_wind,SLP}$  over Europe. (b) Same as (a) but for tp ( $\text{mm day}^{-1}$ ) during the  
 213 50 days displaying the highest  $\alpha_{tp,SLP}$ . (c) Anomalies in  $\alpha_{10m\_wind,SLP}$  observed during the 50  
 214 strongest 10m wind events at each gridbox. (d) Anomalies in  $\alpha_{tp,SLP}$  observed during the 50  
 215 strongest tp events at each gridbox. SLP contours in (a, b) are every 2 hPa (negative dashed).  
 216 Cross-hatching marks regions where at least two thirds of the anomalies shown in colours share  
 217 the same sign. Days with no precipitation are not included in the latter calculation. The colour  
 218 ranges in c, d differ. All  $\alpha$  are computed over 45–60°N 350–20°E (grey box in (a)).

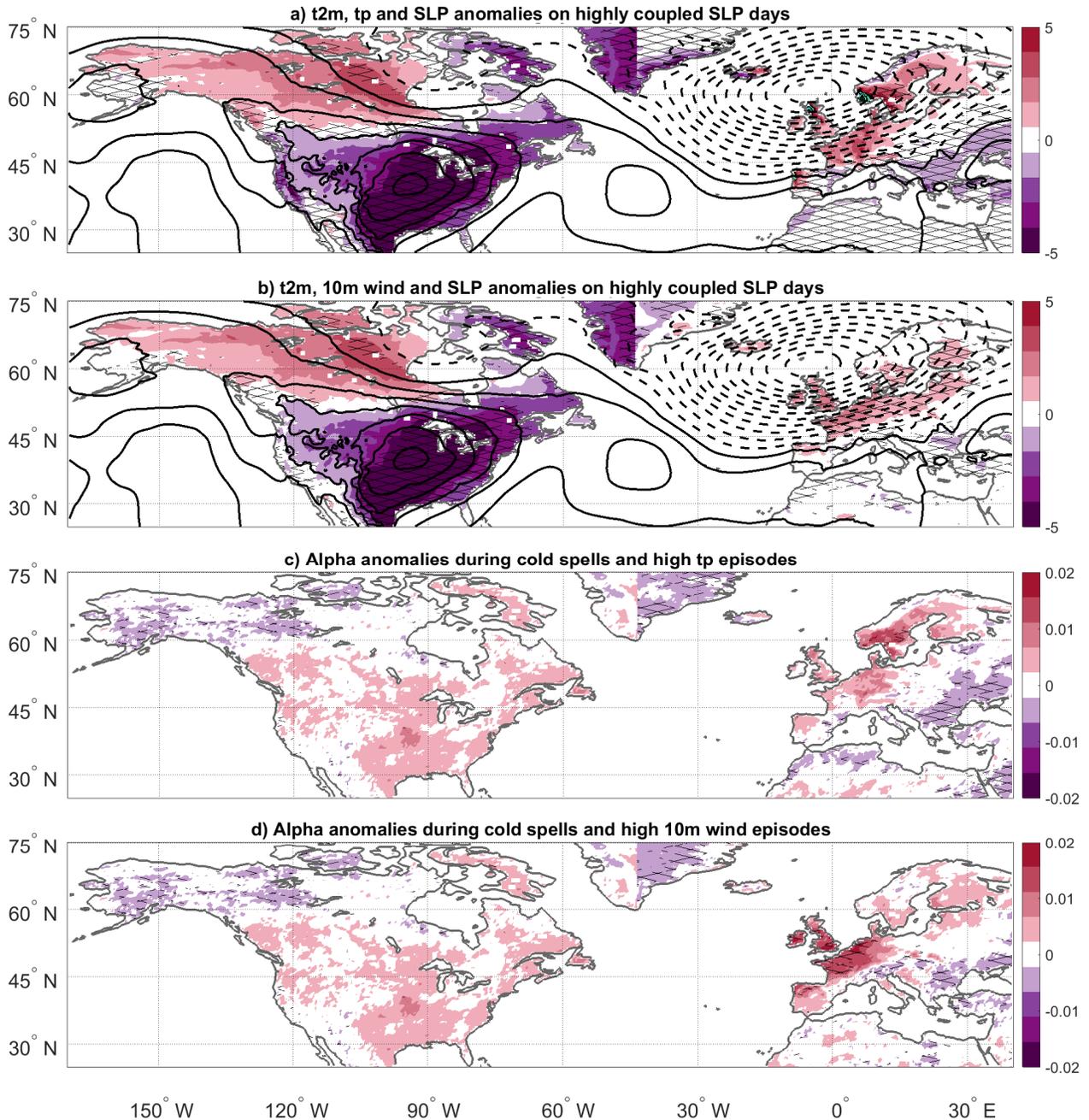
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220 We indeed find that the 50 highest coupling days between SLP and the two impact variables  
 221 correspond to an anomalously high occurrence of 10m wind and tp extremes over regions similar  
 222 to those highlighted in Fig. 2 (Fig. S2b, c). The regions that show strong positive 10m wind and  
 223 precipitation anomalies in Fig. 2a,b also display positive  $\alpha_{10m\_wind,SLP}$  and  $\alpha_{tp,SLP}$  anomalies during  
 224 extremes in the former variables (Fig. 2c, d). In analogy with the cold spells analysis, we  
 225 interpret this as meaning that the surface wind and precipitation extremes in Western Continental

226 Europe share common spatial footprints and are systematically associated with recurrent SLP  
227 configurations. These configurations are similar for the two classes of extremes. We conclude  
228 that the occurrence of wet or windy extremes in Western Continental Europe is associated with a  
229 stronger than usual coupling between SLP and the relevant impact variable. Again, using a larger  
230 SLP domain for computing  $\alpha_{10m\_wind,SLP}$  and  $\alpha_{tp,SLP}$  provides qualitatively comparable results (Fig.  
231 S4).

## 232 **4.2 Compound Cold–Wet–Windy Extremes**

233 We next consider the link between the cold spells over Eastern North America and the wet or  
234 windy extremes over Western Continental Europe. In Sect. 4.1, we showed that the individual  
235 extreme classes display a close coupling of the relevant impact variable with the atmospheric  
236 circulation as diagnosed by SLP. If the North American and European extremes are indeed  
237 linked through a common large-scale circulation anomaly pattern, we would expect that  
238 occurrences of compound cold–wet–windy extremes should match high coupling events between  
239 the SLP patterns in the two continents. We thus compute  $\alpha$  between North American and  
240 European SLP fields. For the 50 highest coupling days, both the SLP anomalies and the t2m,  
241 10m wind and tp anomalies qualitatively match those discussed in Sect. 4.1 (*cf.* Fig. 3a, b with  
242 Figs. 1a and 2a, b). The most notable difference is the absence in Fig. 3a, b of weak negative  
243 SLP anomalies flanking the North American cold spells. However, the key SLP structures such  
244 as the anomalous high over central-eastern North America and the dipole over Europe are very  
245 closely reproduced. Similarly, the t2m, 10m wind and tp anomalies only show minor qualitative  
246 differences (*e.g.* in central-northern Canada), although they are systematically weaker in  
247 magnitude. The same qualitative picture holds if continental-scale domains are used to compute  
248  $\alpha$  between North American and European SLPs. However, the additional information given by  
249 the simultaneous enlargement of both the North American and European domains leads to the  
250 inclusion of SLP structures with little effect on the surface events of interests, and further dilutes  
251 the magnitude of the signal (Fig. S5a, b).

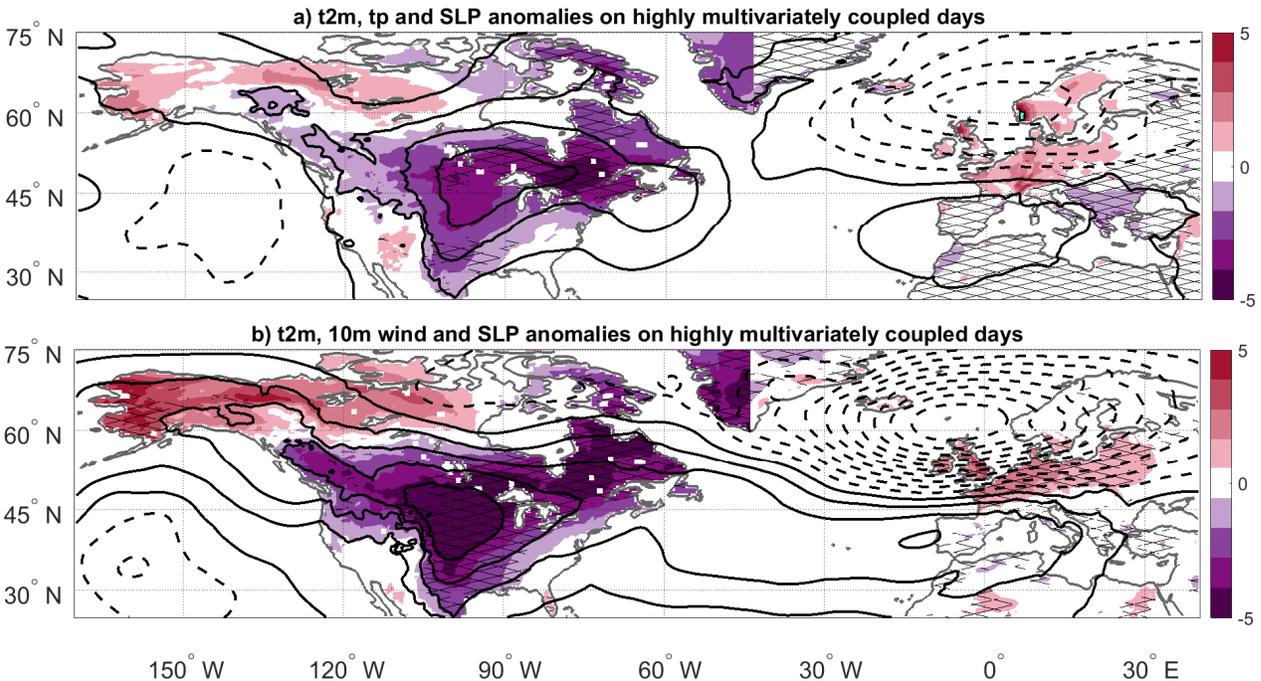


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**Figure 3.** Surface extremes and days with high SLP coupling between North America and Europe. (a) t2m (K) and tp (mm day<sup>-1</sup>) anomalies in colours in the left and right-hand sides of the panel, respectively. SLP (hPa) anomalies are shown in contours every 2 hPa (negative dashed). Anomalies are composited over the 50 days displaying the highest  $\alpha_{SLP1,SLP2}$ , where SLP1 is over 30–45 °N 260–290 °E and SLP2 is over 45–60 °N 350–20 °E. (b) Same as (a) but for 10-metre wind (10m wind, m s<sup>-1</sup>, colours) in the right-hand side of the panel. (c) Anomalies in  $\alpha_{SLP1,SLP2}$  observed during the 50 coldest spells or most extreme 10m wind events at each gridbox in the left and right-hand sides of the panel, respectively. (d) Same as (c) but for the 50 strongest tp events at each gridbox in the right-hand side of the panel. Cross-hatching marks regions where at least two thirds of the anomalies shown in colours share the same sign.

263  
264 The high SLP coupling days between North America and Europe thus show a clear footprint in  
265 the surface anomalies. Moreover, the large-scale SLP patterns in Fig. 3a, b are comparable to  
266 those conditioned on the occurrence of compound cold–wet–windy extremes (Fig. S6). However,  
267 the link between the high SLP coupling days and the local extreme occurrences is considerably  
268 weaker than what observed for the monovariate extremes (*cf.* Figs. 1b, 2c, d and Fig. 3c, d).  
269 Specifically, the anomalies shown in Fig. 3c, d show limited sign agreement, pointing to a large  
270 case-by-case variability. The link between the high SLP coupling days and compound cold–wet–  
271 windy extremes is generally stronger in Europe than in North America, with the latter again  
272 showing limited sign agreement (Table S1).

273 There is thus mixed evidence for the existence of co-recurrent regional or continental-scale  
274 circulation patterns coupled to the compound cold-wet-windy extremes analysed here. This may  
275 be due to  $\alpha$  in Fig. 3 being based only on SLP and not including any of the impact variables. We  
276 thus compute the trivariate co-recurrence for pairs of our impact variables (t2m and tp and t2m  
277 and 10m wind, respectively) and SLP in the respective domains. With the trivariate coupling, we  
278 are requiring a co-recurrence of SLP patterns and surface variable patterns in two different  
279 variables over North American and European domains. We are thus explicitly including  
280 information on both the SLP and the impact variables. The 50 highest trivariate coupling days  
281 display anomalies consistent with those in Fig. 3, albeit somewhat weakened (Fig. 4). The large-  
282 scale SLP patterns are comparable to those conditioned on the occurrence of compound cold–  
283 wet–windy extremes (Fig. S6). A sensitivity test on broader SLP domains over both North  
284 America and Europe is shown in Fig. S7. The link between the high-coupling days and the  
285 compound extremes is again stronger over Europe, although for compound cold–wet extremes  
286 there is a high sign agreement also over North America (Table S1). We do not present here the  
287 alpha anomalies associated with extremes in an impact variable as we now consider more than  
288 one impact variable simultaneously in computing the coupling.



289  
 290 **Figure 4.** Multivariate coupling between SLP and impact variables in North America and  
 291 Europe. As Fig. 3 but for (a)  $\alpha_{SLP,t2m,tp}$  and (b)  $\alpha_{SLP,t2m,10m\_wind}$ , where SLP is taken jointly over  
 292 30–45°N 260–290°E and 45–60°N 350–20°E.  
 293

## 294 5 Discussion and Conclusions

295 We implemented a recently-developed approach from dynamical systems theory, termed *co-*  
 296 *recurrence ratio*, to study the co-occurrence of cold spells in Eastern North America and wet or  
 297 windy extremes in Western Continental Europe. It has previously been hypothesised that these  
 298 events are statistically and physically linked (Messori *et al.*, 2016; De Luca *et al.*, 2020a). In our  
 299 analysis, we presented the first implementation of the co-recurrence ratio in a trivariate setting.  
 300 We framed the study around two questions, namely: whether the individual extreme event  
 301 classes of interest emerge as having a particularly strong coupling to large-scale atmospheric  
 302 patterns; and whether there is evidence for recurrent large-scale circulation patterns linking the  
 303 co-occurrence of these extremes in North America and Europe.

304 The co-recurrence ratio indicates that both cold spells in Eastern North America and wet or  
 305 windy extremes in Western Continental Europe show an unusually strong coupling to recurrent  
 306 large-scale atmospheric patterns. Consistent with past literature, the key large-scale features are  
 307 an anomalous ridge over central North America and an anomalous NAO-like dipole between the  
 308 North Sea and the Mediterranean. Concerning the second question, our analysis suggests a

309 nuanced picture. Days when the SLP patterns over North America and Europe are strongly  
310 coupled display spatially coherent cold North American anomalies and wet or windy European  
311 anomalies, as well as a large-scale circulation resembling that individually associated with cold  
312 extremes in North America and wet or windy extremes in Europe. Nonetheless, the link between  
313 days when the SLP patterns over North America and Europe are strongly coupled and extremes  
314 in the impact variables we consider is modest. Explicitly including the impact variables in the  
315 coupling analysis, by computing a trivariate co-recurrence ratio (between SLP and two of the  
316 impact variables at a time), does not significantly increase the link. Nonetheless, the large-scale  
317 atmospheric pattern on days with a high trivariate co-recurrence ratio is consistent with the  
318 zonal, intense jet that Messori *et al.* (2016) hypothesised was key to connecting surface  
319 anomalies across the North Atlantic (Fig. S8). We thus conclude that compound cold–wet–windy  
320 anomalies are closely associated with a recurrent large-scale atmospheric pattern grounded in a  
321 strong coupling between SLP fields over North America and Europe. The same holds to some  
322 extent for compound cold–wet–windy extremes, albeit with a weaker signal. The fact that the  
323 individual extreme event classes display a stronger coupling to the circulation than the  
324 compound extremes suggests that the latter may be associated with a more varied range of large-  
325 scale physical drivers. A complementary hypothesis is that synoptic-scale drivers which are only  
326 indirectly reflected in the large-scale picture – such as extratropical cyclones in the North  
327 Atlantic – may modulate the extreme events’ co-occurrence.

328 Methodologically, our analysis provides a strong complement to more complex multivariate  
329 spatial extreme value statistical models. It is time-resolved, and as such enables conditioning on  
330 the occurrence of the extremes. Computing the co-recurrence ratio only requires defining one  
331 parameter, namely the percentile defining what a *recurrence* is (see Text S1). In the future, the  
332 same approach may be extended to study lagged co-recurrence, which would allow to make  
333 causality statements. As all approaches, our analysis also displays some caveats. One is the  
334 dependence of the quantitative results on the choice of geographical domain. The co-recurrence  
335 ratio uses information from the full geographical domain considered, and larger domains will  
336 contain information about atmospheric patterns which have little connection with the extremes of  
337 interest, and which dilutes the sharpness of the information provided by the co-recurrence ratio.  
338 Additionally, the theoretical grounding of the calculation of the co-recurrence ratio may pose

339 some challenges to interpreting the results for those not familiar with the founding concepts of  
340 dynamical systems theory.

341 To conclude, our findings contribute to fill existing knowledge gaps on compound cold–wet–  
342 windy extremes in North America and Europe, by considering explicitly extremes in both  
343 continents and the associated atmospheric circulation patterns. Cold spells in Eastern North  
344 America and wet or windy extremes in Western Continental Europe are connected, yet are  
345 governed by a single set of coherent atmospheric circulation patterns. This motivates further  
346 analyses focussing specifically on the statistics and drivers of the compound extremes. We  
347 further conclude that the co-recurrence ratio can provide useful insights for the study of  
348 compound climate extremes, and that several promising additional developments of the  
349 methodology exist.

350

## 351 **Acknowledgments**

352 The authors have no conflicts of interest nor financial conflicts related to this work.

353

## 354 **Open Research**

355 The ERA5 data used in this study is freely available from the Copernicus Climate Change service at:

356 <https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=ERA5>

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*Geophysical Research Letters*

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Supporting Information for

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## **Diagnosing the Systematic Occurrence of Wintertime Compound Climate Extremes in North America and Europe**

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6

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21

### **Introduction**

22

In this Supporting Information, we provide text describing in detail the computation of the co-recurrence ratio (Text S1) and text describing the algorithm to define compound extreme occurrences (Text S3). All supplementary figures and tables which complement the analysis in the main text are described in Text S2.

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#### **Text S1.**

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The computation of  $\alpha$  is grounded in the concept of recurrences, widely used in dynamical systems theory. Given a long trajectory  $\mathbf{x}(t)$  describing the evolution of a stationary chaotic dynamical system (returning to our previous example, this could be a succession of latitude-longitude t2m or SLP maps), one can define logarithmic returns relative to a specific state of interest  $\zeta_x$  (a t2m or SLP map on a specific day) as:

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$$g(\mathbf{x}(t), \zeta_x) = -\log[\text{dist}(\mathbf{x}(t), \zeta_x)]$$

34 Here *dist* is a distance function between two vectors, that tends to zero for increasing  
 35 resemblance. We use the Euclidean distance; the implications of using other distance  
 36 functions are discussed in Lucarini *et al.* (2016) and Faranda *et al.* (2019). Using the  $-\log$   
 37 function makes the timeseries  $g$  large when *dist* is small, namely when we observe a  
 38 recurrence such that  $\mathbf{x}(t)$  resembles  $\zeta_x$ . We next select a threshold  $s(q, \zeta_x)$ , where  $q$  is a  
 39 high quantile of  $g(\mathbf{x}(t), \zeta_x)$  (here  $q=0.98$ ). We define recurrences of  $\zeta_x$  as timesteps  $t_i$  at  
 40 which  $g(\mathbf{x}(t_i), \zeta_x) > s(q, \zeta_x)$ .

41 Given a second trajectory  $\mathbf{y}(t)$  and a state of interest  $\zeta_y$ , one can similarly define a series  
 42  $g(\mathbf{y}(t), \zeta_y)$ , a high threshold  $s(q, \zeta_y)$  and a joint state of interest  $\zeta=(\zeta_x, \zeta_y)$ . For simplicity, we  
 43 hereafter drop the  $\zeta_x$  and  $\zeta_y$  from our notation and append the variables as subscripts. The  
 44 co-recurrence ratio is then given by:

$$\alpha_{x,y}(\zeta) = \frac{v[g(\mathbf{x}(t)) > s_x(q) \cap g(\mathbf{y}(t)) > s_y(q)]}{v[g(\mathbf{x}(t)) > s_x(q)]}$$

45 Here  $v[-]$  denotes the number of events satisfying condition  $[-]$ , and  $0 \leq \alpha \leq 1$ . By  
 46 defining the high thresholds as quantiles of the series  $g$ , we implicitly impose that  
 47  $v[g(\mathbf{x}(t)) > s_x(q)] \equiv v[g(\mathbf{y}(t)) > s_y(q)]$ . Thus,  $\alpha$  is independent of the ordering of the variables,  
 48 and may not be interpreted in terms of causality. For atmospheric variables,  $\alpha$  typically  
 49 takes values of order of  $10^{-2}$  to  $10^{-1}$  (Faranda *et al.*, 2020a; De Luca *et al.*, 2020a, b;  
 50 Messori and Faranda, 2021). The choice of a high  $s(q, \zeta_y)$  to define recurrence implies that  
 51 these are inherently rare, as are joint recurrences. Thus, even relatively low fractions of  
 52 joint recurrences are very unlikely to be obtained by chance. As an example, the  $\alpha_{t2m,SLP}$   
 53 discussed in Sect. 4.1 ranges over  $0 \leq \alpha \leq 0.37$ , while the  $\alpha_{SLP1,SLP2}$  discussed in Sect. 4.2  
 54 ranges over  $0 \leq \alpha \leq 0.13$ .

55 The framework for joint recurrences may be extended to three variables. Given a third  
 56 trajectory  $\mathbf{z}(t)$  and  $\zeta=(\zeta_x, \zeta_y, \zeta_z)$ , one may define:

$$\alpha_{x,y,z}(\zeta) = \frac{v[(g(\mathbf{x}(t)) > s_x(q) \cap g(\mathbf{y}(t)) > s_y(q)) \cap g(\mathbf{z}(t)) > s_z(q)]}{v[g(\mathbf{x}(t)) > s_x(q)]}$$

57 Even in this case,  $\alpha$  is independent of the ordering of the variables. One simply poses the  
 58 additional constraint of a third, simultaneous co-recurrence. This suggests that a trivariate  
 59  $\alpha$  will display lower values than its bivariate counterpart. As an example, the  
 60  $\alpha_{SLP,t2m,10m\_wind}$  discussed in Sect. 4.2 ranges over  $0 \leq \alpha \leq 0.07$ . We underscore that a joint  
 61 recurrence across three variables is an extremely stringent condition, such that the  
 62 trivariate alpha attains low values almost by design. Even seemingly low values are  
 63 therefore highly unlikely to be obtained by chance.

## 64 Text S2.

65 In the supplementary material we present: a table showing co-recurrence ratio anomalies  
 66 during compound extremes; figures showing the SLP, t2m, tp and 10m wind composite  
 67 anomalies for cold spells, tp, 10m wind and compound extremes in the North American  
 68 and European domains we analyse here (Figs. S1, S6); a figure testing the  
 69 correspondence between high-coupling days and (near-)surface extremes (Fig. S2);  
 70 figures testing the sensitivity of our results to the choice of geographical domain (Figs.

71 S3—5, 7); and a figure showing the upper-level flow anomalies associated with the high  
72 coupling days shown in Fig. 4 (Fig. S8).

73 In Figs. S5 and S7, several of the key large-scale features identified in Figs. 3 and 4 are  
74 still evident, but the strong negative t2m signal over North America is partially lost. This  
75 is not surprising: we are simultaneously extending the SLP domains over both North  
76 America and Europe, which adds significant information that may not be directly relevant  
77 to extreme occurrences in the domains of interest, and pushes the limits of the co-  
78 recurrence ratio.

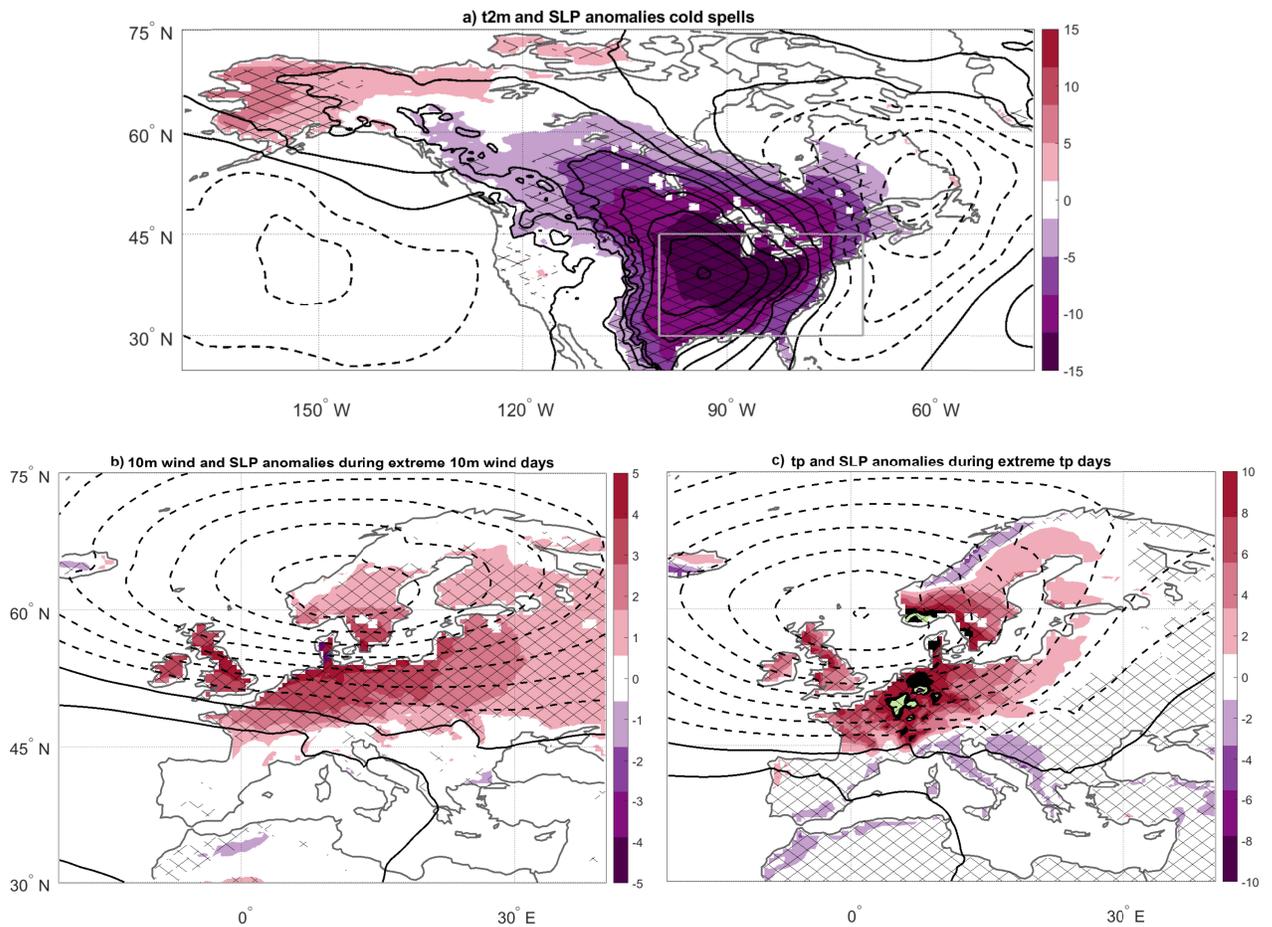
79 Fig. S8 shows a stronger signal on the jet stream of the co-recurrence ratio computed on  
80 10m wind rather than on tp. We speculate that this may depend on the fact that  
81 windstorms are more closely associated with North Atlantic cyclones than heavy  
82 precipitation, which can also be associated with other drivers (*e.g.* lake effect in the  
83 Baltic region).

84

#### 85 **Text S3.**

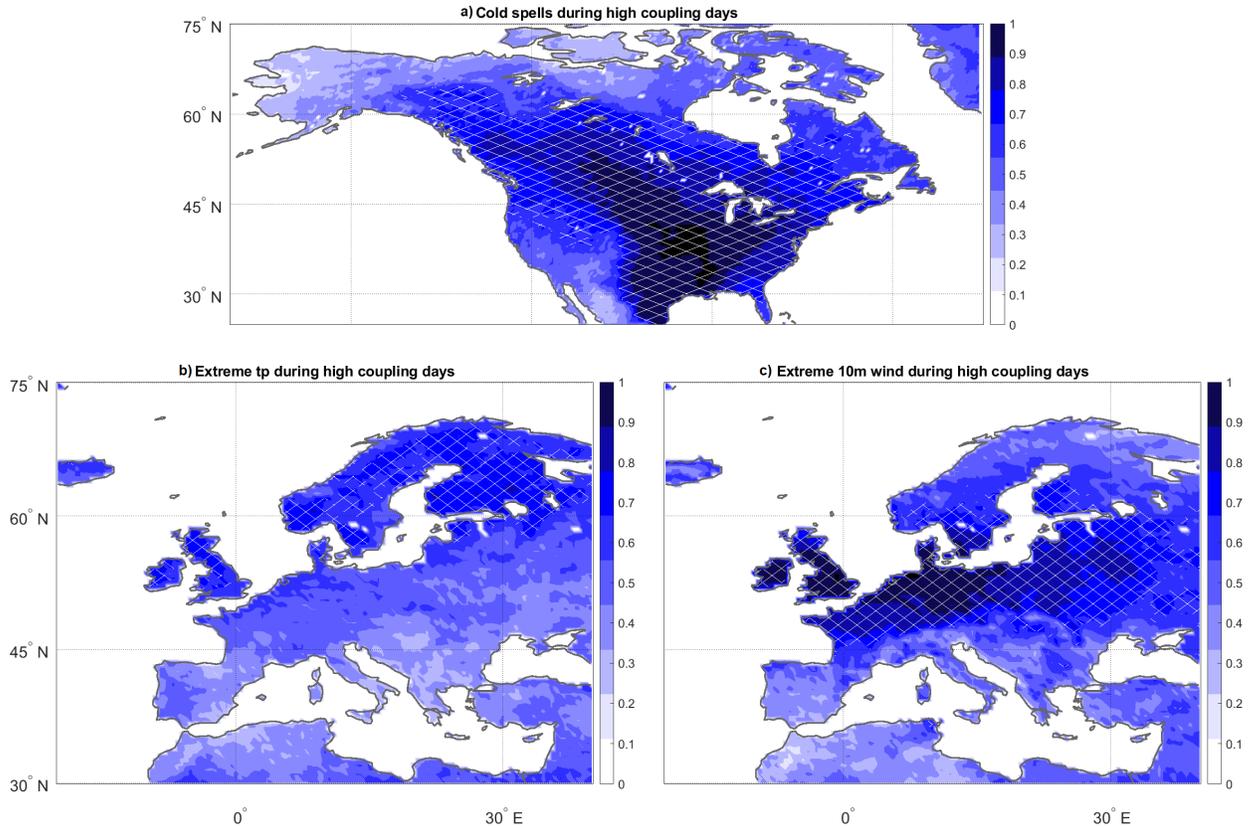
86 Compound extremes in Table S1 and Fig. S6 are identified as area-averaged t2m  
87 extremes in Eastern North America (45–60 °N 350–20 °E), which occur within 5 days of  
88 a tp or 10m wind extreme in Western Continental Europe (45–60 °N 350–20 °E). The  
89 compound extremes are ordered according to the joint rank of the two impact variables  
90 being considered. For example, the 20<sup>th</sup> coldest cold spell matching the 30<sup>th</sup> heaviest  
91 precipitation event will be assigned a joint rank of 50; similarly, the 10<sup>th</sup> coldest cold  
92 spell matching the 32<sup>nd</sup> heaviest precipitation event will be assigned a joint rank of 42 etc.  
93 The top 50 compound cold–wet and cold–windy extremes according to joint rank are  
94 then selected.

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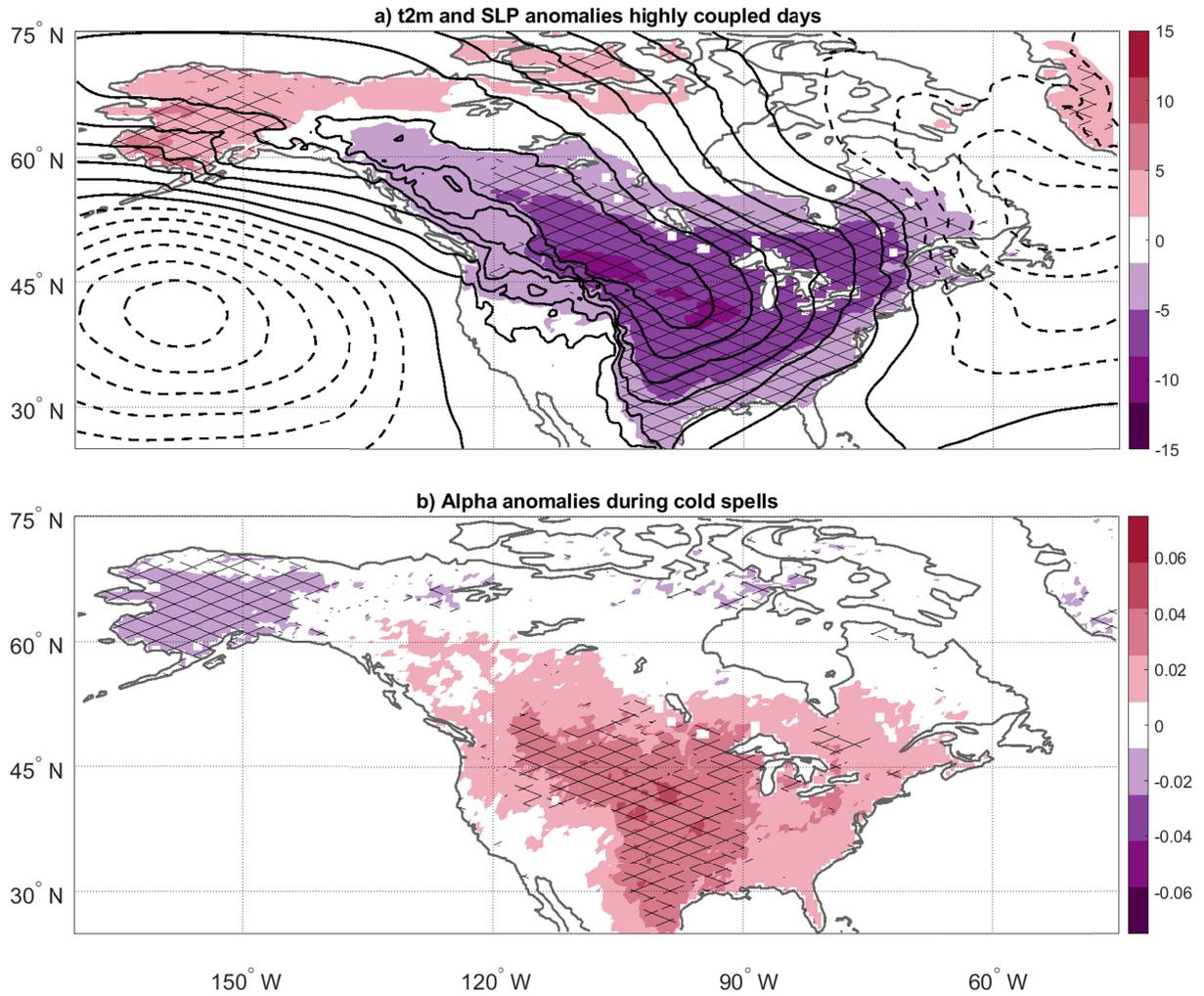
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**Figure S1.** (a) 2-metre temperature (t2m, K, colours) and sea-level pressure (SLP, hPa, contours) anomalies for the 50 coldest cold spells over Eastern North America (grey box in Fig. 1a, 30–45 °N 260–290 °E). (b) Same as (a) but for the 50 strongest 10-metre wind (10m wind, m s<sup>-1</sup>) events over Europe (grey box in Fig. 2a, 45–60 °N 350–20 °E). (c) Same as (b) but for the 50 heaviest total precipitation (tp, mm day<sup>-1</sup>, colours) events.



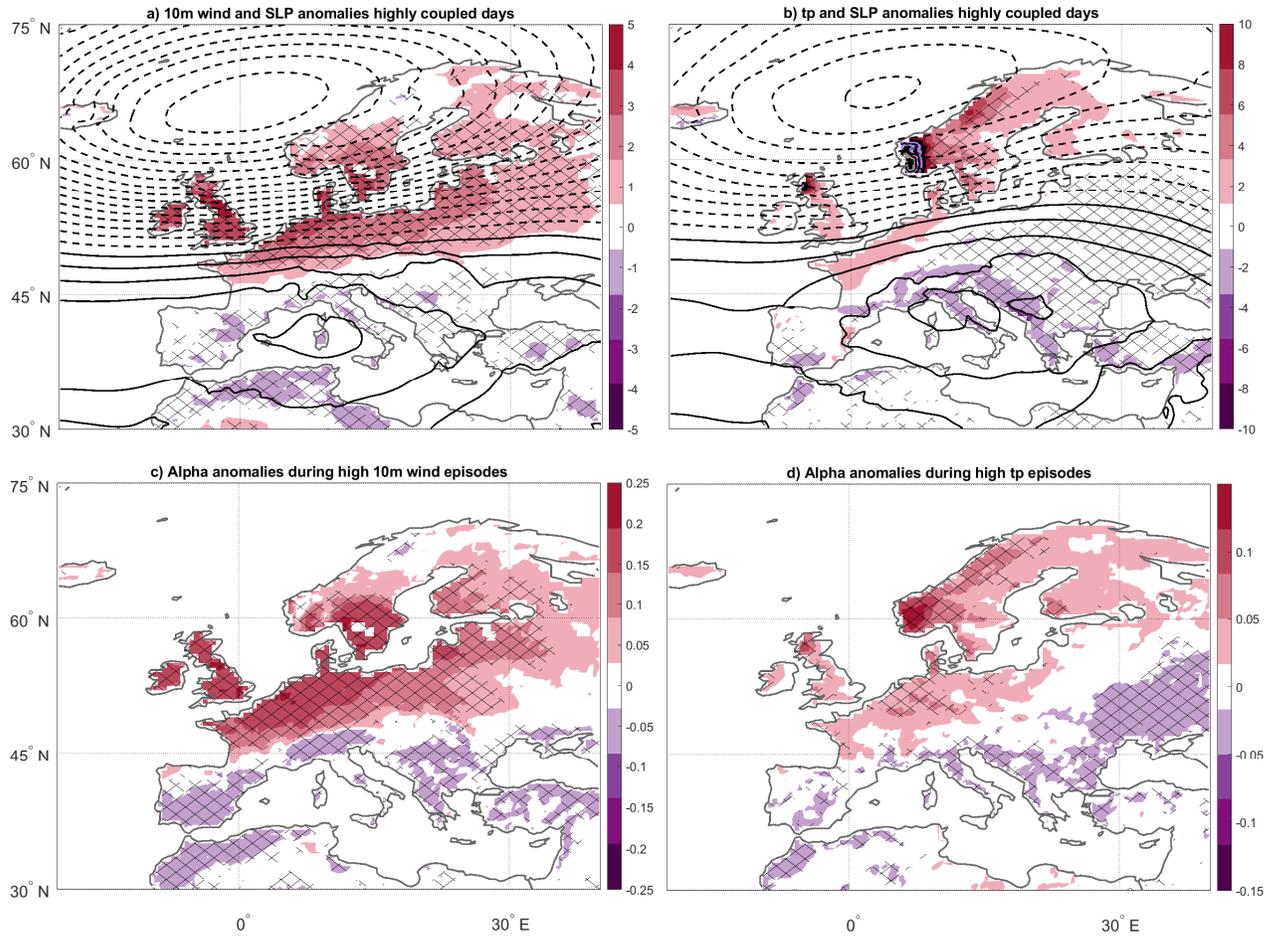
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**Figure S2.** Correspondence between the 50 days displaying the highest coupling and (near-)surface extremes (ranked by area-averaged anomalies over 45–60 °N 350–20 °E (t2m) or 30–45 °N 260–290 °E (tp and 10m wind)). (a) Normalised occurrence of cold spells during high  $\alpha_{t2m,SLP}$  computed over 30–45 °N 260–290 °E. (b) Normalised occurrence of extreme tp during high  $\alpha_{tp,SLP}$  computed over 45–60 °N 350–20 °E. (c) Same as (b) but for extreme 10m wind and  $\alpha_{10m\_wind,SLP}$ . All extremes are defined as the top (bottom for t2m) 5 percentiles of the local distributions, imposing a minimum separation between extremes of 5 days. A high  $\alpha$  value is considered to match an extreme if the latter falls within 5 days of the former. The number of extremes occurring during high  $\alpha$  days is then normalised to [0, 1]. Cross-hatching marks regions where the occurrence of extremes during high  $\alpha$  days is significantly higher than climatology at the 5% one-sided level, determined using 1000 random sampling iterations.



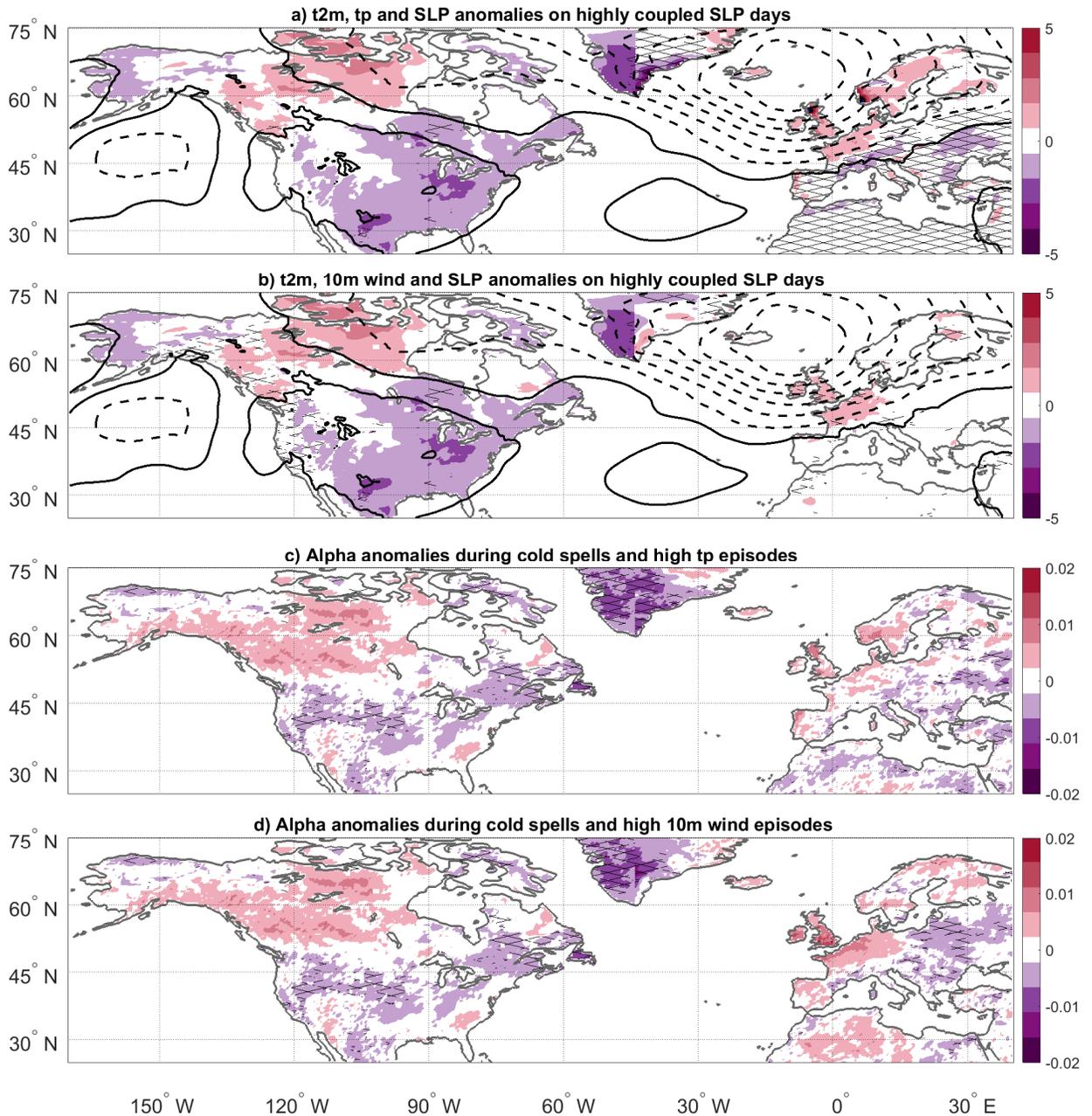
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**Figure S3.** Same as Fig. 1 but for  $\alpha_{t2m,SLP}$  computed using SLP over 25–75 °N 190–315 °E. Note that the colourscale in panel (b) is different from that in Fig. 1b.



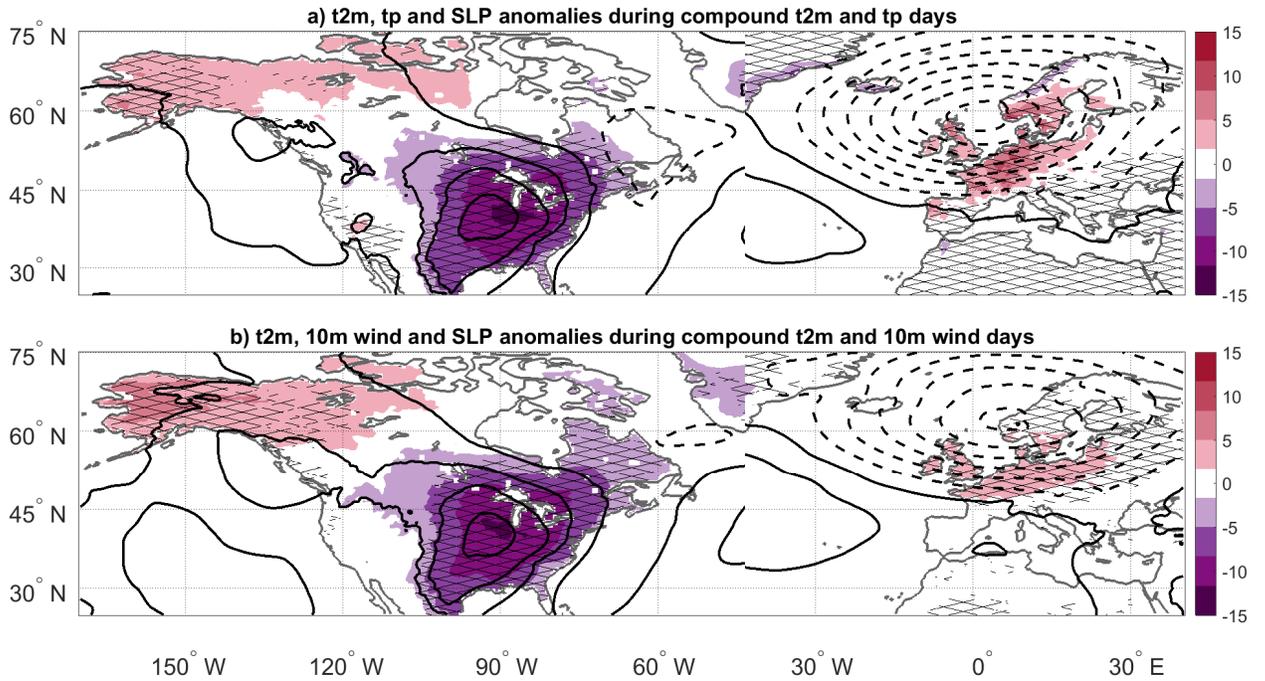
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**Figure S4.** Same as Fig. 2 but for  $\alpha_{10m\ wind, SLP}$  and  $\alpha_{tp, SLP}$  computed using SLP over 30–75 °N 340–40 °E. Note that the colourscale in panel (c) is different from that in Fig. 2c.



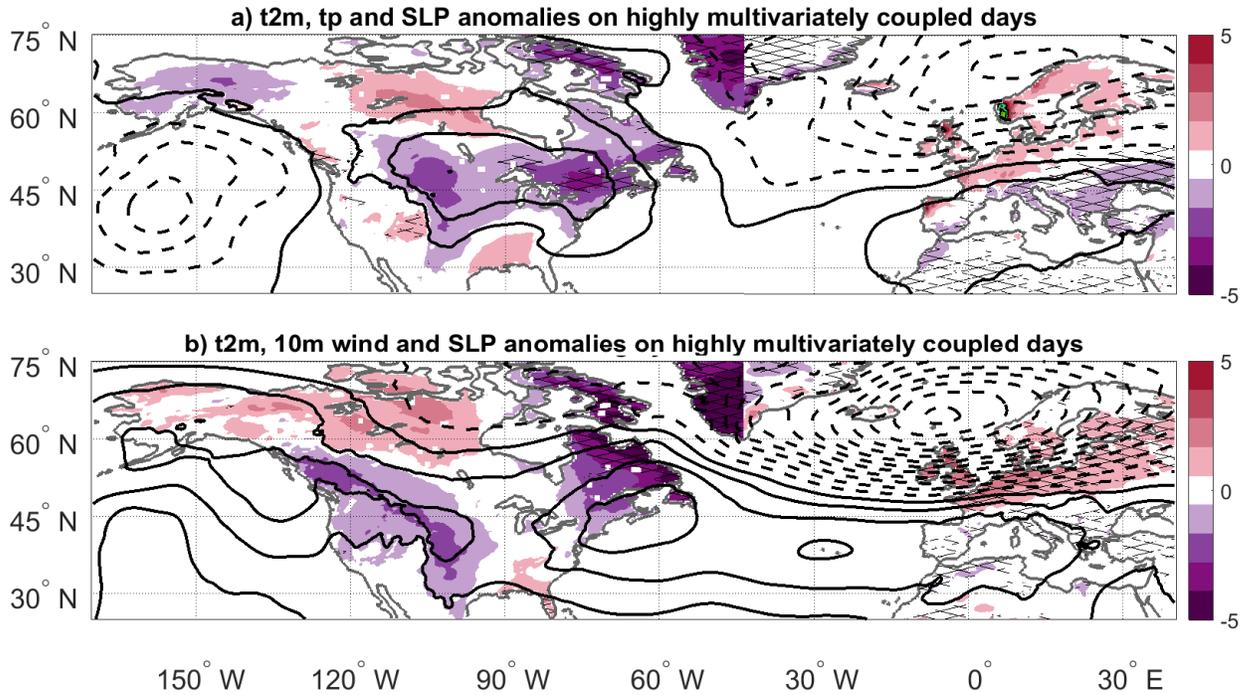
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**Figure S5.** Same as Fig. 3 but for  $\alpha_{SLP1,SLP2}$  computed using SLP over 25–75 °N 190–315 °E and 30–75 °N 340–40 °E.



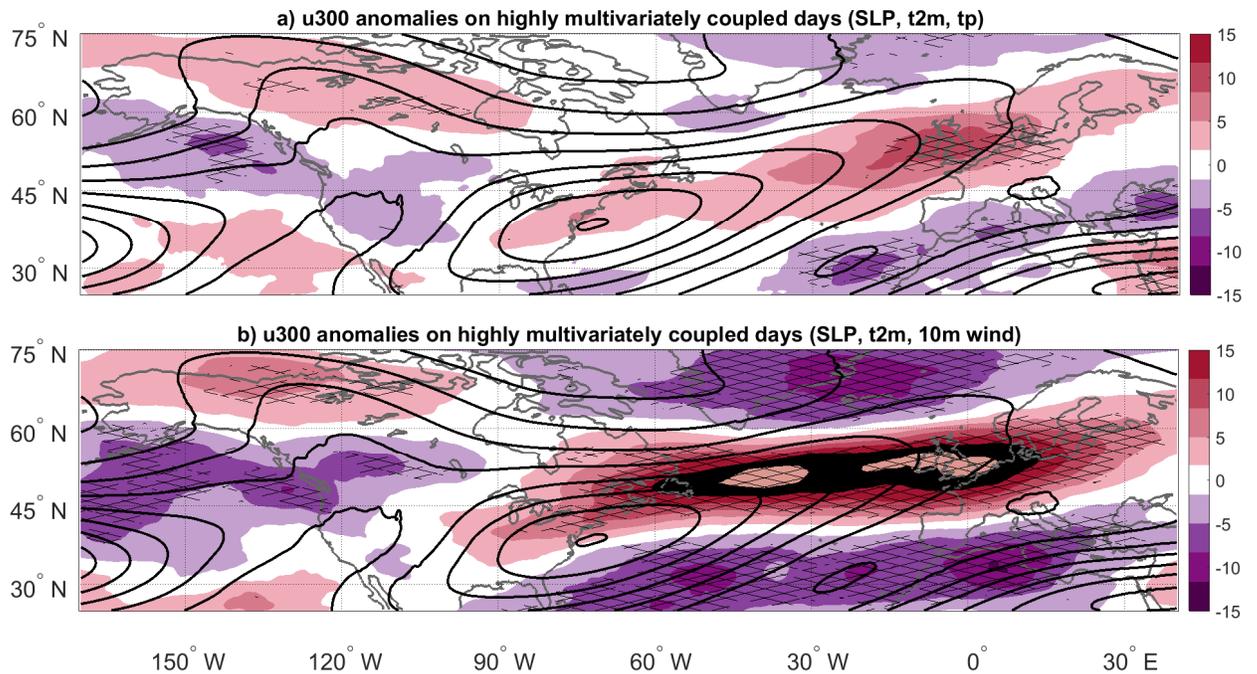
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**Figure S6.** (a) 2-metre temperature (t2m, K) and total precipitation (tp, mm day<sup>-1</sup>) anomalies in colours in the left and right-hand sides of the panel, respectively. Sea-level pressure (SLP, hPa) anomalies are shown in contours every 2 hPa, with negative contours dashed. Anomalies are composited over the 50 strongest compound cold-wet extremes over Eastern North America (grey box in Fig. 1a, 30–45 °N 260–290 °E) and Western Continental Europe (grey box in Fig. 2a, 45–60 °N 350–20 °E). (b) Same as (a) but for 10-metre wind (10m wind, m s<sup>-1</sup>) and for the 50 strongest compound cold-windy extremes. Since this approach allows up to a 5-day shift between the left and right-hand sides of the panels (see Text S3), unlike in other figures the SLP contours do not match at the boundary between the t2m and tp or 10m wind domains.



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**Figure S7.** Same as Fig. 4 but for  $\alpha_{SLP,t2m,tp}$  and  $\alpha_{SLP,t2m,10m\_wind}$  computed using SLP over 25–75 °N 190–315 °E and 30–75 °N 340–40 °E.



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**Figure S8.** 300 hpa zonal wind anomalies ( $u300$ ,  $m\ s^{-1}$ , colours) and climatological DJF zonal wind (contours, every  $2\ m\ s^{-1}$ ) during the 50 highest (a)  $\alpha_{SLP,tp,SLP}$  and (b)  $\alpha_{SLP,10m\_wind,SLP}$  days. Both  $\alpha$  are computed over the same domains as in Fig. 4. Cross-hatching marks regions where at least two thirds of the  $u300$  anomalies share the same sign.

162

163 **Table S1.**  $\alpha$  anomalies during compound extremes, defined as in Text S3. All values are  
 164 rounded to two decimal places. Since the dates of the North American t2m and European  
 165 tp or 10m wind events within each compound extreme can differ by up to 5 days,  
 166 separate  $\alpha$  anomalies for North America and Europe are provided for each  $\alpha$  variable.  
 167 Numbers in bold indicate that more than 2/3 of the  $\alpha$  anomalies for the individual  
 168 compound extremes share the same sign.

$\alpha$ variable	Type of Compound Extreme			
	Cold—Wet		Cold—Windy	
	$\alpha$ anomaly North America	$\alpha$ anomaly Europe	$\alpha$ anomaly North America	$\alpha$ anomaly Europe
$\alpha_{SLP1,SLP2}$ as in Fig. 3	0.01	<b>0.02</b>	0.01	<b>0.02</b>
$\alpha_{SLP,t2m,tp}$ as in Fig. 4	<b>0.01</b>	<b>0.01</b>	—	—
$\alpha_{SLP,t2m,10m\_wind}$ as in Fig. 4	—	—	0.01	<b>0.01</b>

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