

1 **Are the winters 2010 and 2012 archetypes exhibiting extreme**  
2 **opposite behavior of the North Atlantic jet stream?**

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## Abstract

12

13 The atmospheric circulation over the North Atlantic-European sector experienced  
14 exceptional but highly contrasting conditions in the recent 2010 and 2012 winters  
15 (November-March; with the year dated by the relevant January). Evidence is given for  
16 the remarkably different locations of the eddy-driven westerly jet over the North  
17 Atlantic. In the 2010 winter the maximum of the jet stream was systematically between  
18 30°N and 40°N (in the ‘south jet regime’), while in the 2012 winter it was  
19 predominantly located around 55°N (north jet regime). These jet features underline the  
20 occurrence of either weak flow (2010) or strong and persistent ridges throughout the  
21 troposphere (2012). This is confirmed by the very different occurrence of blocking  
22 systems over the North Atlantic, associated with episodes of strong cyclonic  
23 (anticyclonic) Rossby wave breaking in 2010 (2012) winters. These dynamical features  
24 underlie strong precipitation and temperature anomalies over parts of Europe, with  
25 detrimental impacts on many socioeconomic sectors. Despite the highly contrasting  
26 atmospheric states, mid and high-latitude boundary conditions do not reveal strong  
27 differences in these two winters. The two winters were associated with opposite ENSO  
28 phases, but there is no causal evidence of a remote forcing from the Pacific sea surface  
29 temperatures. Finally, the exceptionality of the two winters is demonstrated in relation  
30 to the last 140 years. It is suggested that these winters may be seen as archetypes of  
31 North Atlantic jet variability under current climate conditions.

32

33 **Keywords:** jet stream, blocking, wave-breaking, SPRE, precipitation, North Atlantic-  
34 European sector, extreme winters

35

## 36 1. Introduction

37 Weather and climate over Europe are strongly dependent on the large-scale atmospheric  
38 circulation over the North Atlantic (NA) area (e.g. Wanner et al. 2001). During the two  
39 recent winters of 2009/10 and 2011/12 (hereafter winters 2010 and 2012), the  
40 dynamical conditions over the NA were completely different, showing a dramatic range  
41 of variability in terms of the large-scale atmospheric flow. Therefore, the analysis of  
42 these two highly contrasting winters helps to clarify the mechanisms underlying the  
43 atmospheric variability over the NA under current climate conditions. Among the  
44 possible diagnostics for this variability, the eddy-driven westerly jet is an important  
45 indicator of the physical state of the tropospheric circulation within the Euro-Atlantic  
46 sector. In particular, its latitude and speed have been shown to be suitable measures of  
47 the largest scale circulation over this region (Woollings et al. 2010a). When considering  
48 the jet latitude, the two winters 2010 and 2012 lie at the opposite extremes of the  
49 spectrum of variability, and so it is useful to describe the dynamical features of these  
50 winters as possible archetypes of NA jet variability.

51 The latitude of the NA jet stream and the occurrence of anticyclonic Rossby wave-  
52 breaking (RWB) over southwestern Europe were also shown to be related to strong and  
53 persistent ridge episodes (SPRE) over the eastern NA (Santos et al. 2009; Woollings et  
54 al. 2011). Further, the close relationship between RWB and blocking systems was  
55 already discussed in several previous studies (e.g. Altenhoff et al. 2008; Berrisford et al.  
56 2007; Gabriel and Peters 2008; Pelly and Hoskins 2003; Tyrlis and Hoskins 2008).  
57 Blocking is traditionally identified using indices based on the reversal of the meridional  
58 gradient of the mid-tropospheric geopotential height (e.g. Barriopedro et al. 2006;  
59 Tibaldi and Molteni 1990). The interplays between RWB / blocking and the North

60 Atlantic Oscillation (NAO), the Northern Annular Mode (NAM), the East Atlantic (EA)  
61 pattern or the stratospheric variability have also been widely discussed (e.g. Croci-  
62 Maspoli et al. 2007; Masato et al. 2012; Woollings and Hoskins 2008; Woollings et al.  
63 2008; Woollings et al. 2010b). In a recent study, Davini et al. (2012) underlined the  
64 differences between the (more frequent) high-latitude and mid-latitude blockings (also  
65 called European blockings) in the NA, which are driven by cyclonic and anticyclonic  
66 RWB, respectively (see also Weijenborg et al. 2012).

67 The large-scale atmospheric conditions over the NA are of central importance for the  
68 weather and climate over the European continent. Recent studies show that the  
69 occurrence of weather and climate extremes may have increased on the global scale  
70 (Field et al. 2012). In particular, there is increasing evidence that anthropogenic forcing  
71 is gradually changing both the strength and frequency of temperature and precipitation  
72 extremes (Hansen et al. 2012). The large-scale atmospheric circulation over the NA  
73 strongly controls not only the mean precipitation and temperature fields over Europe,  
74 but also their extremes, particularly in winter, as demonstrated by many previous  
75 studies (e.g. Cattiaux et al. 2012; Efthymiadis et al. 2011; Kenyon and Hegerl 2010;  
76 Santos et al. 2007; Trigo et al. 2004). In fact, wintertime climate variability over most of  
77 Europe is strongly reflected in the NAO and EA phases, which are the leading  
78 teleconnection patterns of the atmospheric variability in the NA-European sector and  
79 closely related to jet variability (Hurrell et al. 2001; Pinto and Raible 2012; Wallace and  
80 Gutzler 1981; Wanner et al. 2001). As persistent anomalies in the atmospheric flow  
81 over the NA-European sector tend to yield extremes of precipitation and/or temperature  
82 over parts of Europe (e.g. Andrade et al. 2012; García-Herrera et al. 2007; Mahlstein et  
83 al. 2012), the understanding of their driving mechanisms can provide valuable  
84 information for improving seasonal forecasts and climate change projections, both of

85 which are of significant value for many socioeconomic sectors. As a result of the  
86 anomalies in the large-scale circulation in the 2010 and 2012 winters, strong anomalies  
87 in both precipitation and temperature were recorded all across Europe. While the 2010  
88 winter was anomalously wet over southern Europe (Andrade et al. 2011; Vicente-  
89 Serrano et al. 2011) and was also characterized by strong cold outbreaks in northern  
90 Europe (Moore and Renfrew 2012; Wang et al. 2010), the 2012 winter was anomalously  
91 dry in southern Europe and anomalously warm in northern Europe, as will be shown  
92 below. As such, the present study also aims to systematize some dynamical features  
93 associated with the occurrence of near surface atmospheric extremes over Europe on a  
94 seasonal basis.

95 In this study, the main goals are twofold: 1) to provide further insight into the  
96 dynamical features of these extreme winters; 2) to give a long-term perspective of their  
97 likelihood and exceptionality. An underlying motivation is to assess the extent to which  
98 these winters may be seen as archetypes of NA jet variability. The manuscript is  
99 organized as follows: data and methods are described in section 2. The results are  
100 presented and discussed in section 3. Lastly, section 4 presents an overview of the most  
101 significant outcomes and conclusions.

102

## 103 2. Data and methods

104 The *National Centers for Environmental Prediction* (NCEP) / *National Center for*  
105 *Atmospheric Research* (NCAR) reanalysis dataset (Kistler et al. (2001); hereafter  
106 NCEP-NCAR reanalysis) in the period 1950-2012 is used for characterizing the large-  
107 scale atmospheric circulation in the winters of 2010 and 2012. This dataset has a spatial  
108 resolution of  $2.5^\circ$  latitude  $\times$   $2.5^\circ$  longitude and a temporal resolution of 6 h. Unless

109 otherwise stated, NCEP data is used. The *European Centre for Medium-range Weather*  
110 *Forecasts* (ECMWF) ERA-Interim reanalysis (Dee et al. 2011), with atmospheric fields  
111 on a  $1.5^\circ$  latitude  $\times$   $1.5^\circ$  longitude grid and at a 6-hourly time resolution, is also used as  
112 a basis for the characterization of the 2-PVU (Potential Vorticity Unit) potential  
113 temperature during the two selected winters. This dataset is improved with respect to  
114 the ECMWF ERA-40 reanalysis (Uppala et al. 2005) and is regularly updated. The  
115 period analyzed is November-March.

116 Furthermore, the NA eddy-driven jet latitude characterization and the SPRE detection  
117 are also carried out using the *Twentieth Century Reanalysis* (Compo et al. (2011);  
118 hereafter 20CR). As this dataset comprises information on the uncertainty of the  
119 atmospheric fields, by providing a 56-member ensemble over a relatively long time  
120 period (1871-2010; 140 years), it allows estimations of the uncertainties inherent to  
121 each diagnostic. The 20CR fields are defined on a  $2^\circ$  latitude  $\times$   $2^\circ$  longitude grid at 6-  
122 hourly time spacing. As the 20CR is mainly used to provide a long-term perspective of  
123 the range of variability of the features analyzed in the present study (jet index and  
124 SPRE), it is not a major shortcoming that data for the 2012 winter is not available.

125 The jet index, the blocking classification and the SPRE detection are used herein as  
126 diagnostic tools of the large-scale atmospheric flow over the eastern NA. The jet index  
127 computation is described in Woollings et al. (2010a). Essentially the method determines  
128 an average jet latitude and speed across the NA, by averaging the zonal wind over 0-  
129  $60^\circ$ W and smoothing with a 10-day low-pass filter before finding the maximum speed.  
130 In the original method, the zonal wind was additionally averaged over pressure levels  
131 between 925 and 700 hPa. Here, however, only the 850 hPa level has been used, as it is  
132 the only isobaric level within the 925-700 hPa layer available in the 20CR. A

133 comparison between the jet indices calculated using either 850 hPa or 925-700 hPa has  
134 been made using ERA-40 data, but very similar results are obtained (not shown). The  
135 rationale of this approach is to isolate the eddy-driven component of the zonal flow by  
136 using only lower tropospheric data. Woollings et al. (2010a) provided evidence that the  
137 jet latitude variability projects both onto the NAO and EA patterns. As such, the method  
138 provides physical quantities which describe much of the same variability as the NAO  
139 and EA.

140 The blocking detection method is taken from a previous study by Scherrer et al. (2006).  
141 This index is a straightforward extension of the classical Tibaldi and Molteni (1990)  
142 index into two dimensions (latitude and longitude). The index has the advantage that it  
143 can be readily calculated from reanalysis data using daily mean 500 hPa geopotential  
144 heights. It is very similar to the index used by Davini et al. (2012) and gives a similar  
145 climatology of blocking to that of Masato et al. (2012). Both of the classical constraints  
146 are applied: 1) that the meridional geopotential height gradient is reversed at a given  
147 point and 2) that the flow is westerly to the north of the point, with a height gradient  
148 stronger than 10 m per degree of latitude. Finally, a 5-day persistence criterion is  
149 applied to each grid point before it can be considered as part of a block. Note that the  
150 region identified as blocked corresponds roughly to the location of the anticyclone of  
151 the blocking dipole, rather than the location of flow reversal as in some other indices.

152 The SPRE are identified following the same methodology as in Santos et al. (2009) and  
153 Woollings et al. (2011), but for an extended wintertime period (November-March) and  
154 using the 500 hPa geopotential height (Z500) rather than the 250 hPa geopotential  
155 height. The choice of a different isobaric level enabled a direct comparison among  
156 different datasets (in particular, the 250 hPa level is not available in the 20CR for all

157 ensemble members). Nevertheless, there is a high consistency between results using  
158 these two isobaric levels (not shown). Herein, a SPRE corresponds to an episode that  
159 persists at least 10 days with a Z500 zonal mean departure, averaged over the sector  
160 [40-50°N, 40°W-5°E], higher than 140 gpm. This threshold approximately corresponds  
161 to the 60<sup>th</sup> percentile of the distribution of the wintertime zonal mean departures over  
162 the baseline period of 1950-2012. It guarantees that only strong ridge events are  
163 considered, but with a sufficiently high number of episodes being isolated. The zonal  
164 departures are computed with respect to a second-order polynomial adjusted to the daily  
165 climate-means (baseline period of 1950-2012) of the Z500 zonal-means over the full  
166 winter period (1<sup>st</sup> of November to 31<sup>st</sup> of March). All SPRE are separated by at least 3  
167 days. A list of 85 SPRE in the period 1950-2012 is provided in Table S1, together with  
168 their corresponding onsets and decays, lengths (in days) and strengths (area-means of  
169 the zonal mean departures).

170 The cyclone activity for the two winters was quantified by a cyclone tracking algorithm,  
171 originally developed by Murray and Simmonds (1991) and adapted for the NA cyclone  
172 characteristics by Pinto et al. (2005). The methodology was applied to the NCEP-  
173 NCAR reanalysis over the baseline period in order to compute the cyclone track density  
174 and the corresponding anomalies for the two selected winters. The method compares  
175 well with results by other tracking methods and is able to follow cyclones from the early  
176 stages of cyclone development until dissipation (Neu et al. 2013).

177 In summary, three reanalysis databases (NCEP-NCAR, ERA-Interim and 20CR) are  
178 used in the present study so that several diagnostics can be calculated and compared,  
179 making use of their different advantages and availabilities. The ERA-Interim reanalysis  
180 provides improved atmospheric fields at relatively high spatial resolution. However,



181 owing to its short period of available data (1979-2012) other reanalysis need to be  
182 considered so as to improve the statistical significance of the results (larger sample  
183 sizes). This constraint explains the preferential use of the NCEP-NCAR reanalysis and  
184 of the 20CR within the scope of the present study.

185

### 186 3. Results

#### 187 *a. Jet signatures*

188 The highly contrasting atmospheric conditions during the two recent winters  
189 (November-March) of 2010 and 2012 are clearly manifested by in the jet stream  
190 features. The latitude-time Hovmöller diagrams of the 850 hPa zonal wind component,  
191 averaged within the 0-60°W longitude sector (central and eastern NA), clearly highlight  
192 the different dynamical regimes that prevailed in the two winters (left panels in Fig. 1).  
193 The axis of the maximum westerly flow (illustrated by the daily latitudes of the zonal  
194 wind maxima) is within the latitude sector of 30-50°N most of the time in the 2010  
195 winter, while it tended to be polewards of the 50°N parallel in the 2012 winter. In both  
196 winters the westerly flow is generally strong on a daily basis (20-30 m s<sup>-1</sup>) and is  
197 flanked by comparatively weak easterly flows at higher and lower latitudes.

198 The corresponding histograms of the jet latitude index (right panels in Fig. 1) reveal that  
199 the jet is often close to its southernmost (northernmost) location in the winter of 2010  
200 (2012). In fact, the jet location is almost always equatorwards of the 50°N parallel  
201 during the 2010 winter, particularly from mid-December onwards, while in the 2012  
202 winter it is mostly located polewards of the 50°N parallel, predominantly from late  
203 November to late March. Furthermore, taking into account the robustness of the

204 trimodal distribution of the jet latitude (preferred locations) in winter (Woollings et al.  
205 2011; distributions shown in their Fig. 1), it can be stated that during the winter of 2010  
206 both the southern and mid-latitude flow regimes are dominant, while in 2012 the  
207 northern flow is by far the leading regime. The most pronounced exceptions to these  
208 general features occurred in early December 2009 and late January 2010 (in the 2010  
209 winter), when the jet was in its northern flow regime, and in November 2011 and March  
210 2012 (in the 2012 winter), when the jet was temporarily shifted southwards. The close  
211 relationship between the jet latitude over the NA and the NAO phase is also reflected in  
212 the strong phase opposition of the NAO pattern during the two winters (November-  
213 March): -1.18 (2010) and +1.35 (2012). In fact, these extreme values correspond to the  
214 5th (2010) and 98th (2012) percentiles of the full distribution of the November-March  
215 mean NAO in 1950-2012, according to the Climate Prediction Center (CPC) NAO  
216 index (<http://www.cpc.ncep.noaa.gov/>). If the shorter season of December-February is  
217 considered instead, the negative NAO of the 2010 winter becomes more extreme  
218 (Osborn 2011).

219

## 220 *b. Dynamical diagnosis*

221 The longitude-time Hovmöller diagrams of the daily 500 hPa geopotential height  
222 anomalies from the instantaneous zonal-mean, averaged within the latitude sector of 40-  
223 50°N and for the winters of 2010 and 2012, underline their remarkably different  
224 dynamical characteristics (Fig. 2). Strong negative anomalies are found over the NA  
225 (90-30°W) in the 2010 winter, while the persistence of the strong positive anomalies  
226 over the Eastern NA (40°W-5°E) is very pronounced in the 2012 winter. For both  
227 winters, the eastwards propagation of high-frequency anomalies from the eastern North

228 Pacific (120-180°W) towards the NA (0-60°W) is also found. The connections between  
229 the NA sector and the North Pacific mid-latitudes have been discussed in previous  
230 studies (Castanheira and Graf 2003; Honda et al. 2005; Pinto et al. 2011).

231 For the 2012 winter, the strong cores of positive anomalies over the Eastern NA divert  
232 the mid-latitude low pressure systems, and their associated fronts, to higher latitudes,  
233 leading to a blocking of the eastward traveling cyclones (Rex 1950). The blocking  
234 frequencies for each winter hint at the very different conditions in the 2010 and 2012  
235 winters (Fig. 3). While in 2010 blocking occurrences over the NA were anomalously  
236 high (low) polewards (equatorwards) of the 60°N parallel, a nearly opposite pattern  
237 occurred in 2012. Blocking was therefore prevalent in both winters with the difference  
238 being that this lay largely on the north side of the southward displaced jet in 2010 and  
239 largely on the south side of the northward displaced jet in 2012. In fact, blocking  
240 occurred over Scotland and southern Scandinavia in both winters, although with the jet  
241 lying to the south in 2010 and to the north in 2012. In the northeastern region of Europe,  
242 the blocking anomalies are actually quite similar for the two winters. This region  
243 appears to be far enough downstream that the blocking is more or less independent of  
244 the Atlantic jet position.

245 The strong blocking over and near Greenland in 2010 is consistent with the strongly  
246 negative NAO in this winter, since these two features are closely related in general  
247 (Crocì-Maspoli et al. 2007; Woollings et al. 2008). Woollings et al. (2011) found that  
248 while blocking over southern Europe does tend to accompany the SPRE and northward  
249 Atlantic jet shifts, the relationship is less strong than that between Greenland blocking  
250 and southward jet shifts. It is interesting that the overall picture is of as much blocking  
251 in 2012 as in 2010, with equally large blocking anomalies in both winters. At least for

252 these extreme cases then, it seems that blocking can be important for both northward  
253 and southward shifts of the jet. Also note that, as in Davini et al. (2012), the index used  
254 here finds more blocking events at lower latitudes than the PV-based index of  
255 Woollings et al. (2011), which may be a factor here.

256 The contrasting dynamical features can also be emphasized by the unprecedented high  
257 number of SPRE days in the winter of 2012 (70 days), while the winter of 2010 shows  
258 no SPRE occurrences (Table S1). The dynamical conditions underlying the SPRE are  
259 highlighted by the composites of the 500 hPa geopotential height and temperature  
260 anomalies only for SPRE days, along with the corresponding 250 hPa geopotential  
261 height anomalies (cf. Fig. S1 in supplemental material). As expected, taking into  
262 account the SPRE definition, a positive anomaly with a nearly equivalent barotropic  
263 structure is apparent over the Eastern NA. Note that the maximum positive anomaly in  
264 the 500 hPa geopotential height (nearly 140 gpm; Fig. S1) is lower than the average  
265 strength of the SPRE (about 214 gpm; Table S1). In fact, owing to the climate-mean  
266 ridge over the eastern NA, the zonal mean departures of the 500 hPa geopotential height  
267 used in the SPRE definition are predominantly higher than the temporal anomalies at  
268 each grid point over the same region. A negative and westward tilted with height  
269 (baroclinic) anomaly can also be found over higher latitudes, as well as a second  
270 positive core over North America. The composite for the 250 hPa streamlines (Fig. S1)  
271 not only gives evidence for a blocking of the westerly flow over Europe, but also  
272 suggests the presence of anticyclonic RWB. This is in line with the previous findings  
273 that wave-breaking acts to amplify the SPRE anomaly and likely increase its persistence  
274 (Woollings et al. 2011). Furthermore, the overall dynamical structure of the SPRE  
275 (equivalent barotropic ridges), as well as the associated anticyclonic RWB, are in clear  
276 agreement with both the NA low-latitude blocking and the European blocking discussed

277 by Davini et al. (2012). Since the SPRE are defined as geopotential anomalies  
278 northwards of the 40°N parallel, they conform more to the so-called European  
279 blockings, which can actually block the prevailing westerly flow (rather than divert it).  
280 Although further research is needed to improve the current understanding of the  
281 mechanisms underlying the SPRE onset, development and decay, such a dynamical  
282 attribution analysis is out of the scope of the present study, as the SPRE classification is  
283 here used only as a diagnostic tool to characterize the atmospheric conditions over the  
284 study area.

285 The composites of the potential temperature on a 2-PVU surface (near the tropopause  
286 level) clearly highlight the remarkable differences between these two winters (Fig. 4). In  
287 fact, the mean flow is largely zonal over the eastern NA in 2010, suggesting high  
288 transiency, while it presents a strong ridge with a southwest-northeast tilt over the same  
289 region in 2012, this time suggesting a relatively high stationarity in the flow over the  
290 eastern NA. This ridge in the mean flow is indeed a manifestation of strong and  
291 frequent anticyclonic RWB in the 2012 winter. This statement can be clearly illustrated  
292 for a 3-day period in the 2012 winter (2-4 December 2011; Fig. 4, based on ERA-  
293 Interim), when a large-scale anticyclonic meridional overturning of the 2-PVU potential  
294 temperature is apparent. It starts with a major poleward advection of a relatively warm  
295 (subtropical) air mass that is followed by anticyclonic RWB (Fig. 4). The anticyclonic  
296 RWB in the following days underlies the persistence of this strong eddy, justifying its  
297 classification as a SPRE (number 83; Table S1 in supplemental material). This event  
298 effectively corresponds to a 10-day length SPRE (1-10 December 2011) with 215 gpm  
299 strength. Similar considerations can be extrapolated to many other days during the 2012  
300 winter (not shown), taking into consideration that 70 days out of 152 (November-  
301 March) were keyed as SPRE days (Table S1). On the other hand, an episode of cyclonic

302 RWB over high latitudes of the NA (30 January-3 February 2010; Fig. 4) demonstrates  
303 the opposite conditions in the 2010 winter. This period shows a large mass of  
304 subtropical, high potential temperature air advecting northward and overturning  
305 cyclonically, in the process of forming a cut-off anticyclone over Greenland. This event  
306 is a classic example of the cyclonic wave-breaking associated with the negative NAO  
307 phase (Benedict et al. 2004; Woollings et al. 2008).

308 The cyclone track densities and the corresponding anomalies for the two winters are in  
309 close agreement with the flow characteristics described above (Fig. 5). Anomalous  
310 high cyclone track densities are found over the eastern NA, Western Europe and the  
311 Mediterranean Basin in 2010, whereas anomalously low densities can be found over the  
312 British Isles, the eastern NA and parts of central Europe. In both winters, opposite  
313 anomalies can be found over the high-latitude NA, mainly in the vicinity of Iceland. It is  
314 interesting that the Mediterranean storm track is not anomalously weak in 2012, and  
315 even shows above average cyclone activity over the Eastern Mediterranean.

316 As a result of the aforementioned shifts in the jet location, and associated changes in the  
317 frequencies of occurrence of cyclones over the NA, the resulting patterns of the total  
318 winter precipitation are remarkably different between the two winters, largely reflecting  
319 the mean path of the westerly jet in each winter (Fig. 5). While the axis of maximum  
320 precipitation over the NA was largely zonal (along the 40°N parallel) in the 2010  
321 winter, it was southwest-northeastwardly tilted in the 2012 winter. As such, the 2010  
322 winter was anomalously dry (wet) over some areas of northern (southern-central)  
323 Europe, whereas nearly the opposite occurred in the 2012 winter. More specifically,  
324 these differences are particularly strong over the mid-latitude NA and southwestern  
325 Europe and, with opposite signal, over the high latitudes of the NA and the Norway-

326 Norwegian Sea region. With respect to the 2 m air temperature anomalies, the contrast  
327 between the two winters is remarkable (Fig. 5). The 2010 winter was anomalously cold  
328 over Northern Europe and along the mean path of the cyclone track and warm over  
329 northeastern Canada and North Africa. Nearly the opposite pattern occurred in the 2012  
330 winter. These precipitation and temperature anomalies are in clear agreement with the  
331 differences in the large-scale circulation over the NA in the two winters.

332 An obvious question is whether there were any strong anomalies in boundary conditions  
333 which could have helped to cause the atmospheric anomalies. It should always be  
334 remembered that extreme events can arise from purely chaotic atmospheric dynamics,  
335 so that a forcing external to the atmosphere is not necessary in general. Recent work by  
336 Jung et al. (2011) suggested that the extreme negative NAO winter of 2010 was not  
337 predictable, at least by their model experiments using several potential driving  
338 mechanisms. However, there is considerable evidence that variations in boundary  
339 conditions do have some influence on interannual variability over the North Atlantic  
340 (e.g. Greatbatch et al. 2012). Here we simply compare and contrast some of the  
341 anomalous boundary conditions for these winters and discuss their potential roles.

342 Regarding the sea surface temperature (SST) anomalies for the two winters, an  
343 important external forcing of the atmospheric circulation, important differences can be  
344 found in the tropical Pacific, as well as in the subtropical NA (Fig. 6a, b). In the 2010  
345 winter a positive El-Niño Southern Oscillation (ENSO; Peixoto and Oort,1992) pattern  
346 is accompanied by an anomalously warm subtropical NA, while in the 2012 winter a  
347 negative ENSO pattern can be found with no significant anomalies in the subtropical  
348 NA. The opposite phases of ENSO are confirmed by the Oceanic Niño Index (ONI) of  
349 the CPC (<http://www.cpc.ncep.noaa.gov/>) which has values of +1.6 and -0.9 for

350 December-February 2010 and 2012, respectively. In contrast, the SST anomalies for  
351 both winters are very similar in the mid-latitude NA and in the Arctic. Furthermore, the  
352 Arctic ice cover leading both winters (October-November) is also very similar (not  
353 shown). Therefore, it is unlikely that mid and high-latitude boundary conditions can  
354 explain the strong differences between the two winters.

355 However, the contrasting remote boundary conditions in the tropical Pacific are  
356 plausible driving mechanisms, as suggested by several previous studies (Müller et al.  
357 2008; Trenberth et al. 1998). In fact, the composite anomalies of the 250 hPa zonal  
358 wind component and of the 500 hPa geopotential heights (Fig. 6c, d) show similar  
359 anomalies spanning the Pacific and Atlantic basins. In the 2010 winter there is a tripole  
360 in the wind anomalies over the NA, with its mid-latitude positive anomalies extending  
361 upwind towards the North Pacific. The Aleutian low is also anomalously weak and the  
362 pattern in the NA clearly reflects the negative NAO phase. On the other hand, in the  
363 2012 winter, the signals of the wind anomalies are generally reversed and are in  
364 conformity with an anomalously strong Aleutian low and a positive NAO phase (cf.  
365 Woollings et al. 2011, their Fig. 6c). It is possible that a connection between the ENSO  
366 phase and the NA flow could have occurred through the Pacific-North American Pattern  
367 (PNA; Wallace and Gutzler 1981). Many previous studies have identified several  
368 mechanisms that could explain North Pacific-NA (NP-NA) coupling such as this  
369 (Castanheira and Graf 2003; Honda et al. 2005; Pinto et al. 2011). A major sudden  
370 stratospheric warming (SSW) was also recorded in the 2010 winter (Dornbrack et al.  
371 2012), as also reported by the NOAA<sup>2</sup>. The occurrence of a SSW has been associated  
372 with NP-NA coupling, mainly through vertical Rossby wave propagation and

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<sup>2</sup> NOAA Weather Service - Climate Prediction Center; <http://www.cpc.ncep.noaa.gov/products/stratosphere/>



373 troposphere-stratosphere coupling (Ineson and Scaife 2009), and with tropospheric  
374 blocking (Castanheira and Barriopedro 2010).

375 A brief statistical analysis has been performed and this reveals no clear signature in the  
376 Pacific SSTs in other winters with very strong Atlantic jet anomalies (not shown). This  
377 demonstrates that there is not a general and permanent link between these features. In  
378 fact, a possible ENSO-like influence has been suggested to be non-stationary in time  
379 due to modulation by multi-decadal oscillations of SST anomalies over the Atlantic and  
380 Pacific basins (e.g. Greatbatch et al. 2004; Zanchettin et al., 2008; López-Parages and  
381 Rodríguez-Fonseca, 2012). Numerical modeling experiments would be required to  
382 investigate the likelihood of tropical Pacific influence in these two winters more fully.

383

#### 384 *c. Assessing the exceptionality of the two winters*

385 As previously mentioned, the 20CR is also used so as to better assess the variability in  
386 both the jet stream latitude and in the number of SPRE days, by using a 56-member  
387 ensemble over a relatively long time period (1871-2010; 140 years). Figure 7a shows  
388 box plots of the winter mean jet latitude, derived by averaging the daily values over the  
389 November-March period. This shows similar empirical distributions for the NCEP-  
390 NCAR reanalysis and the 20CR, despite the larger sample size in 20CR (140 winters)  
391 than in NCEP (63 winters). These distributions are nearly symmetric (almost zero  
392 skewness) and only one outlier is observed for the NCEP distribution (from the NCEP-  
393 NCAR reanalysis). The mean jet latitudes are 41°N in 2010 and 53°N in 2012, which are  
394 located at the very tails of both distributions, particularly in 2010 (Fig. 7a). The strong  
395 dependency of the SPRE detection on fixed thresholds (area-mean Z500 zonal mean  
396 departures greater than 140 gpm, lasting at least 10 days and separated by at least 3

397 days) explains the strong positive skewness in their distributions (Fig. 7b); the skewness  
398 coefficient is statistically significant at a confidence level of 99%. The existence of  
399 several positive outliers in the 20CR distribution is also noteworthy, showing strong  
400 variability in this diagnostic. As previously stated, the winter of 2012 exhibits the  
401 highest number of SPRE days (3 SPRE with a total of 70 days) of the entire record for  
402 the NCEP distribution and corresponds to a positive outlier in the 20CR distribution  
403 (Fig. 7b). On the contrary, the winter of 2010 shows no SPRE occurrences (Fig. 7b), i.e.  
404 the absolute minimum in both distributions, by definition of the SPRE. These findings  
405 are indeed a manifestation of extraordinarily anomalous dynamical conditions that  
406 prevailed during the two winters.

407 In the analysis of the temporal variability for 20CR, medians across the ensemble are  
408 used instead of means, as they are a more robust central tendency measure than the  
409 latter (they are less sensitive to outliers), though the results remain nearly unchanged  
410 (not shown). The chronograms of the jet latitude (Fig. 7c) and of the number of SPRE  
411 days (Fig. 7d) reveal a clear agreement between both reanalysis datasets (NCEP and  
412 20CR) in their common period of 1950-2010 (grey vs. black bars and orange vs. red  
413 curves in Fig. 7c, d). This high correspondence for the jet latitude is corroborated by a  
414 correlation coefficient between its 11-yr moving averages for NCEP and 20CR of 0.99  
415 (statistically significant at a confidence level of 99%). For the number of SPRE days,  
416 the correlation coefficient is 0.94, also statistically significant at a confidence level of  
417 99%. As referred to above, due to the SPRE definition, which relies on specific spatial  
418 and temporal criteria, slight differences in the daily Z500 fields explain some important  
419 discrepancies not only amongst the 20CR ensemble members, but also between 20CR  
420 and NCEP-NCAR outcomes.

421 The chronograms also reveal the presence of slight long-term trends in the ensemble  
422 medians of the two measures (red curves in Fig. 7c, d). In both the mean jet latitude and  
423 in the number of SPRE days, the 11-yr moving averages of the ensemble medians only  
424 show relatively weak decadal trends. The blue lines in turn give an indication of  
425 changes in inter-annual variability over time. This is done by taking the median across  
426 the ensemble as before, but this time plotting the 25<sup>th</sup> and 75<sup>th</sup> percentiles of the set of  
427 11 years in the moving window, hence summarizing the inter-annual variability in each  
428 11 year window. These show that these two extreme winters do not seem to be part of a  
429 long term trend towards higher inter-annual variability. Despite the upward trend in the  
430 number of NCEP SPRE days in the recent past (Fig. 7d), only a slight upward long-term  
431 trend (about + 0.8 day/decade) is found over the whole 140-yr period (1871-2010), or  
432 even in the common period (1950-2012), using 20CR. This discrepancy can be  
433 explained by the stronger linear trend in the Z500 for NCEP than for the 20CR within  
434 the ridge sector of the SPRE definition (not shown). Furthermore, a spectral analysis of  
435 the time series of the individual ensemble members and of the ensemble mean shows no  
436 statistically significant periodicity apart from red-noise in both the jet latitude and in the  
437 number of SPRE days (not shown). This outcome highlights the irregularity (low serial  
438 correlations) in the occurrence of SPRE days.

439

#### 440 4. Summary and conclusions

441 Two recent and exceptional winters within the NA-European sector were selected in the  
442 present study, with clear contrasts in their jet stream latitudes (Fig. 1): 2010  
443 (southwardly shifted jet and frequent high-latitude blocking) and 2012 (northwardly  
444 shifted jet and frequent low-latitude blocking). Owing to their strong impacts on many

445 socioeconomic sectors throughout Europe (strong precipitation and temperature  
446 anomalies), their driving atmospheric dynamics deserve a better understanding, as well  
447 as the assessment of their exceptionality, which are indeed the main purposes of this  
448 research. An analysis of the tropospheric flow hints at strong negative anomalies within  
449 the latitude sector of 40-50°N during the 2010 winter, whilst persistent and recurrent  
450 positive anomalies are found during the 2012 winter for the same latitudes (Fig. 2).  
451 These results are not only confirmed by the extreme NAO phases of the two winters,  
452 but also by the respective blocking frequencies (Fig. 3) and the SPRE occurrences  
453 (Table S1). The characteristic dynamical structure of the SPRE (Fig. S1), with a strong  
454 and persistent equivalent barotropic ridge over the eastern NA, maintained by  
455 anticyclonic RWB, was predominant in the 2012 winter (Figs. S1 and 4). Furthermore,  
456 the southwardly (northwardly) displaced jet in 2010 (2012) is reflected at the surface by  
457 similarly shifted paths of cyclone activity and corresponding precipitation anomalies  
458 over different parts of Europe (Fig. 5). The impacts of these shifts in the large-scale  
459 atmospheric flow on the precipitation totals for each winter are remarkable (Fig. 5). As  
460 a result, a diagnosis of the atmospheric conditions during these two winters elucidated  
461 the role played by the occurrence (absence) of three deeply intertwined dynamical  
462 features (SPRE / low-latitude blocking / anticyclonic-RWB) in triggering extreme  
463 winter conditions in Europe.

464 In most regards the two winters can be seen to be exact opposites of each other.  
465 Furthermore, they are both exceptional events, lying at the extreme opposite ends of the  
466 spectrum of variability. Therefore, these two winters may be seen as prime examples, or  
467 archetypes of the range of NA jet variability, at least under recent and current climate  
468 conditions.

469 The winters of 2010 and 2012 had significant impacts on precipitation and temperature  
470 over large areas of Europe. The contrasts are particularly noticeable between  
471 southwestern and northern Europe (Fig. 5). Despite the extreme nature of these two  
472 winters, the attribution of a single extreme event to either natural variability or  
473 anthropogenic forcing remains a difficult task in climate research (Seneviratne 2012).  
474 Nevertheless, some efforts have been recently made in order to address this issue, such  
475 as in explaining several extreme events that occurred worldwide during the year 2011  
476 (Peterson et al. 2012). Furthermore, the observational precipitation data hint at a global  
477 intensification of the extremes in both tails of the precipitation distributions in the  
478 second half of the twentieth century (Min et al. 2011). In spite of the high complexity  
479 of the mechanisms governing precipitation and the resulting uncertainty in its climate  
480 change projections, enhanced extreme precipitation is expected in a future warmer  
481 climate (e.g. Field et al. 2012; Trenberth et al. 2003). Nonetheless, due to the relatively  
482 poor ability of climate models in reproducing blocking (Matsueda et al. 2009), the  
483 future projections and implications for precipitation are still challenging. As GCMs  
484 generally do not capture the full range of jet variability seen in observations (Anstey et  
485 al. 2013; Barnes and Polvani 2013; Hannachi et al. 2013), this raises concerns over their  
486 ability to predict changes in extreme regional precipitation. In forthcoming research it is  
487 aimed to specifically address this issue using control and forced runs from state-of-the-  
488 art climate models.

489

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499

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- 675

## 676 **List of Figures**

677 FIG. 1. Left panels: Hovmöller diagrams (latitude-time) of the 850 hPa zonal wind  
678 component (in m.s-1), averaged over the 60°W-0° longitude sector for the winters  
679 (November-March) of 2010 and 2012. In both diagrams dark lines indicate the daily  
680 latitudes of zonal wind maxima. Right panels: Corresponding histograms of the jet  
681 latitudinal distributions for the winters of 2010 and 2012 (grey bars), along with the  
682 average histogram over all winters in the period from 1950 to 2012 (white bars). The  
683 frequencies of occurrence of each class are in days winter-1.

684 FIG. 2. Hovmöller diagrams (longitude-time) of the daily 500 hPa geopotential height  
685 anomalies (in gpm) from the instantaneous zonal mean, averaged over the 40-50°N  
686 latitude sector, and for the winters (November-March) of (a) 2010 and (b) 2012.

687 FIG. 3. Left panels: Frequencies of occurrence of blocking (in percentage of days) over  
688 the North Atlantic and Europe for the winters (November-March) of (a) 2010 and (c)  
689 2012. Right panels: Anomalies from climatology (1950-2012) of the blocking  
690 frequencies in (b) 2010 and (d) 2012, on the same color scale.

691 FIG. 4. First row panels: Composites of the 2-PVU potential temperature (in K) for the  
692 winters (November-March) of (a) 2010 and (b) 2012. Dashed line indicates the ridge  
693 axis. Lower left panels: Illustration of a cyclonic RWB episode in the 2-PVU potential  
694 temperature (in K) at 12:00 UTC for the period from 30 January 2010 to 3 February  
695 2010. Lower right panels: Illustration of an anticyclonic RWB episode for the period 2-  
696 4 December 2011 (part of the 83rd SPRE in Table S1).

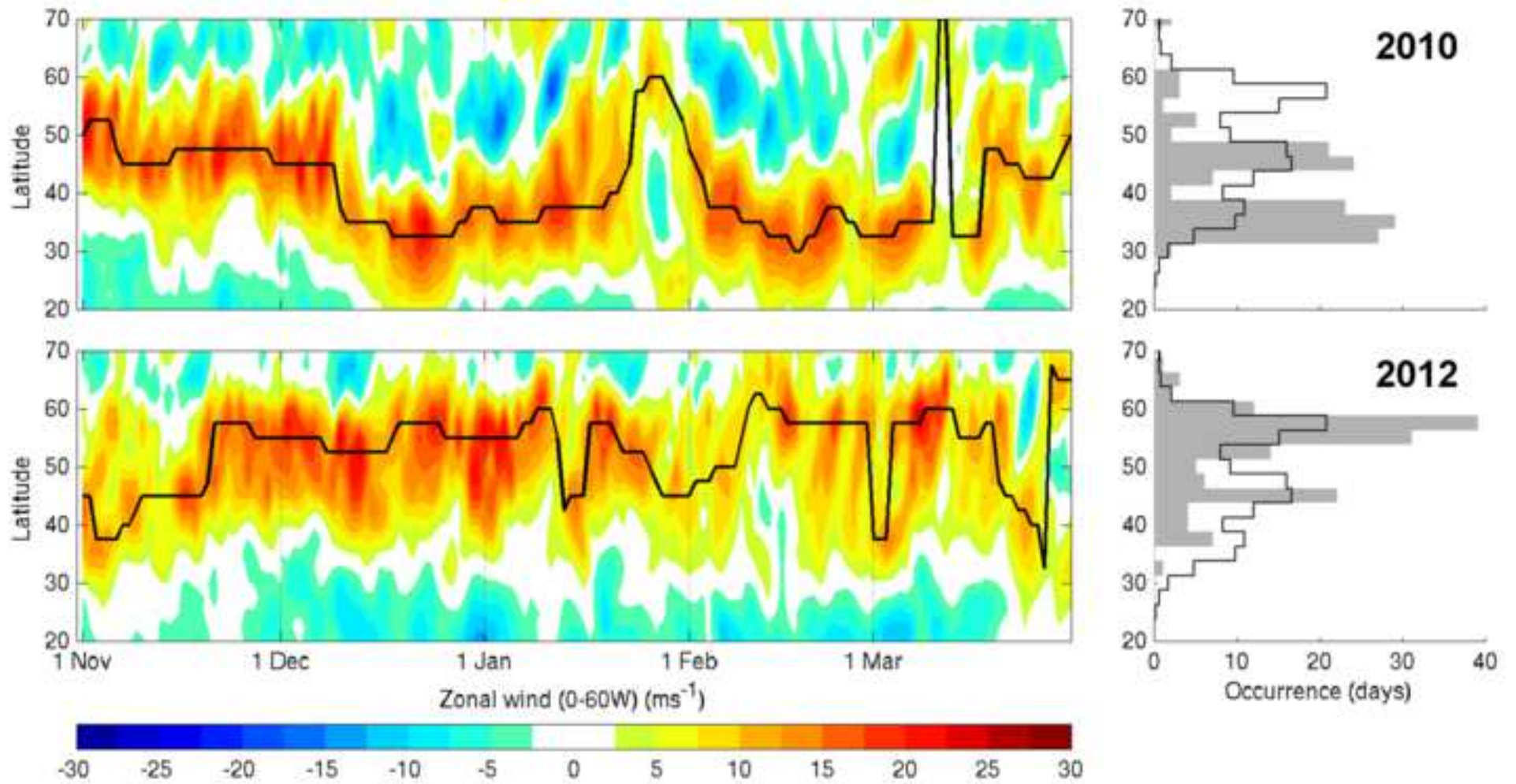
697 FIG. 5. Upper panels: Mean cyclone track density (contours) for the winters  
698 (November-March) of (a) 2010 and (b) 2012 and corresponding anomalies (shading) for

699 the 1950-2012 baseline period. Middle panels: the same as on the upper panels, but for  
700 the mean precipitation rates (in mm day<sup>-1</sup>). Lower panels: the same as on the upper  
701 panels, but for the mean 2 m air temperature (in C°).

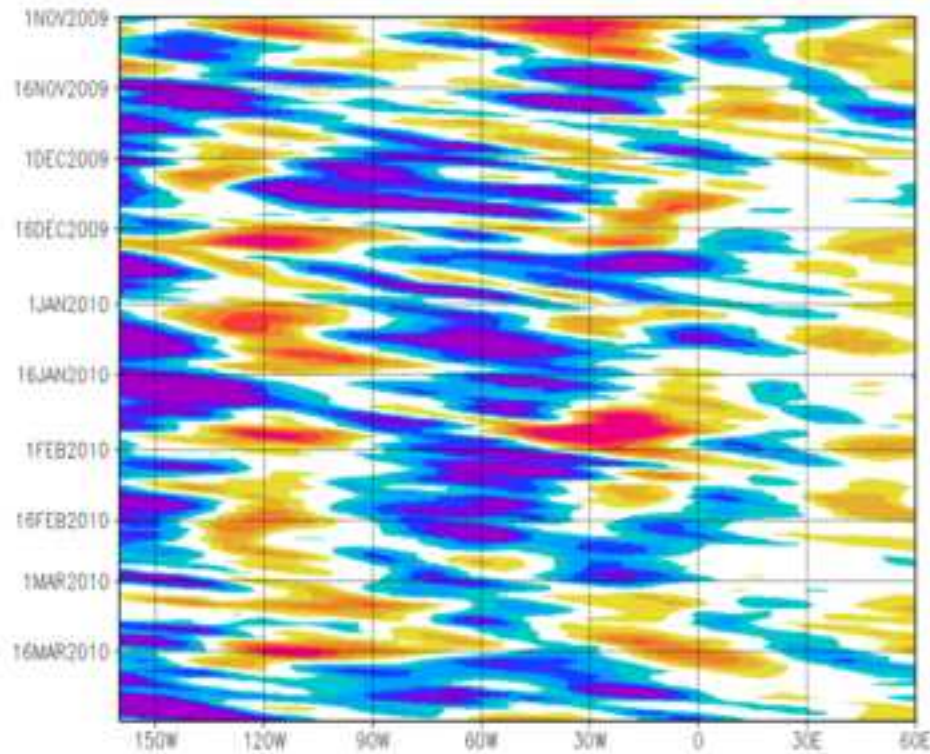
702 FIG. 6. Composite anomalies (baseline period of 1981-2010) of the: SST (shading in  
703 °C) for October-November (a) 2010 and (b) 2012 (from NOAA Extended SST); 250  
704 hPa zonal wind component (shading in m s<sup>-1</sup>) and 500 hPa geopotential height  
705 (contours in gpm) for November-March (c) 2010 and (d) 2012.

706 FIG. 7. Box plots of the (a) jet latitude and (b) number of SPRE days for all winters  
707 (Nov-Mar) in 1950-2012 (NCEP) and 1871-2010 (20CR). Horizontal lines within the  
708 boxes indicate the medians, upper (lower) box limits the first (third) quartiles, upper  
709 (lower) whiskers the non-outliner maxima (minima). Red circles for outliers (above the  
710 3th quartile + 1.5 × interquartile range). Grey arrows locate the 2010 and 2012 winters  
711 in the distribution. Chronograms of the (c) mean jet latitude and (d) number of SPRE  
712 days for winters in 1950-2012 (NCEP-NCAR reanalysis; black bars) and corresponding  
713 ensemble medians for winters in 1871-2010 (20CR; grey bars). Years refer to January  
714 of each winter. The 11-yr running means (red curves) and the 11-yr running first/third  
715 quartiles (blue curves) of the ensemble medians are plotted, along with the 11-yr  
716 running means for the NCEP-NCAR (orange curves).

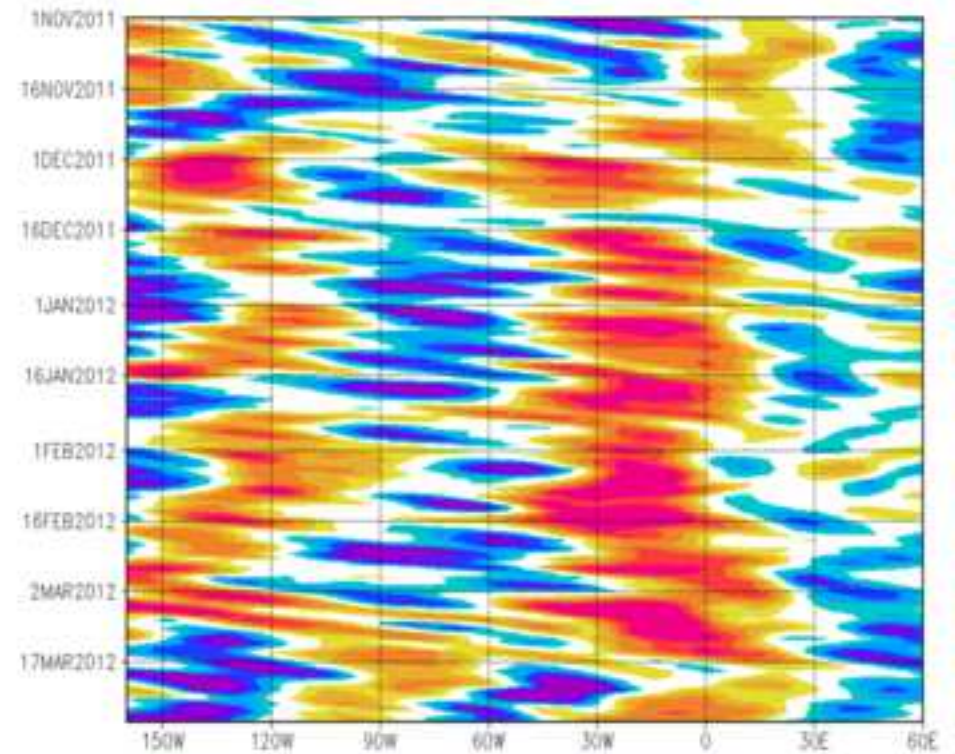
Rendered Figure 1  
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(a) 2010



(b) 2012

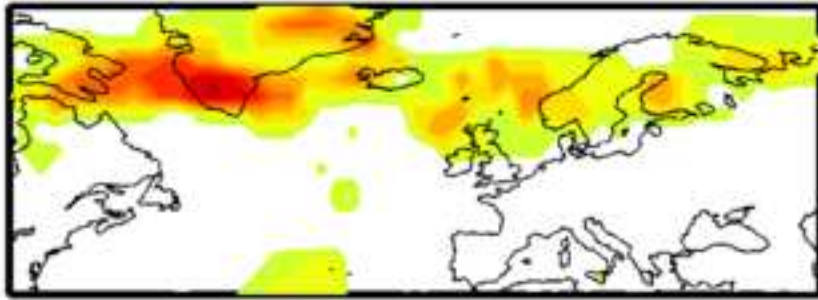


Geopotential height anomalies (gpm)

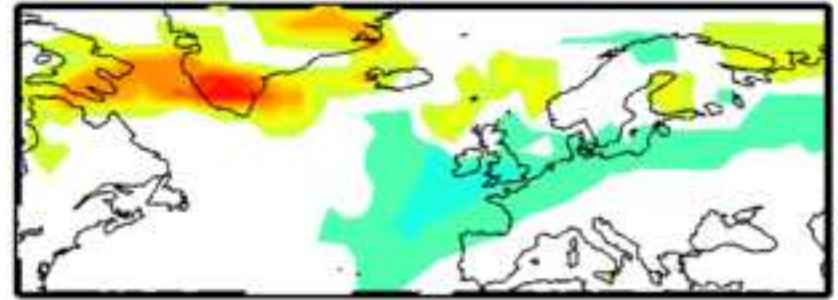




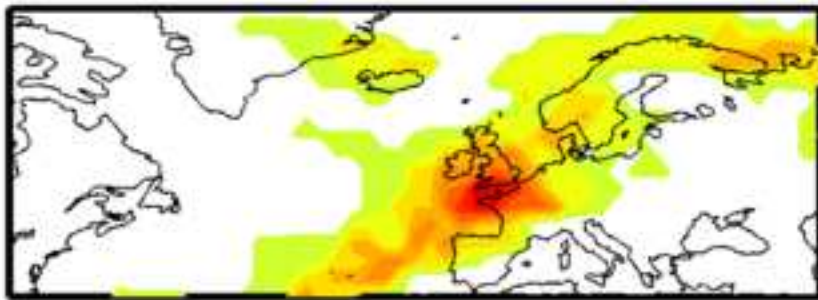
(a) 2010



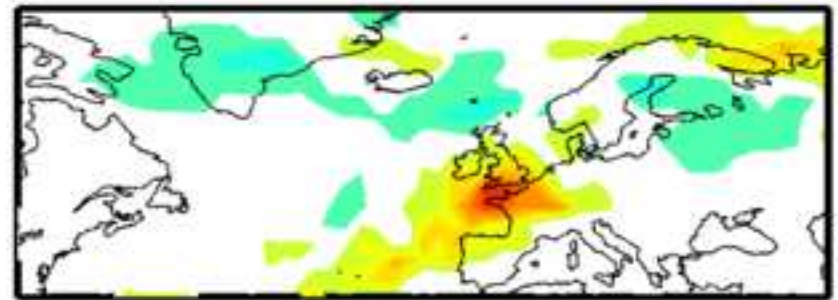
(b) 2010 anomalies



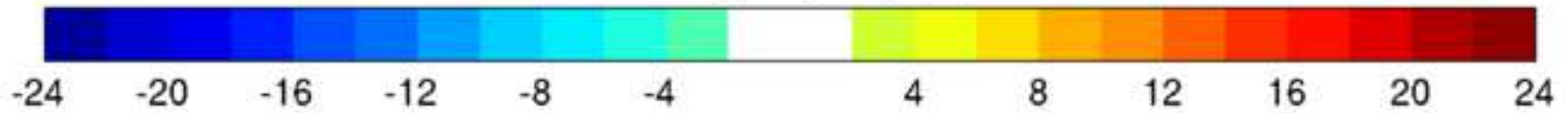
(c) 2012

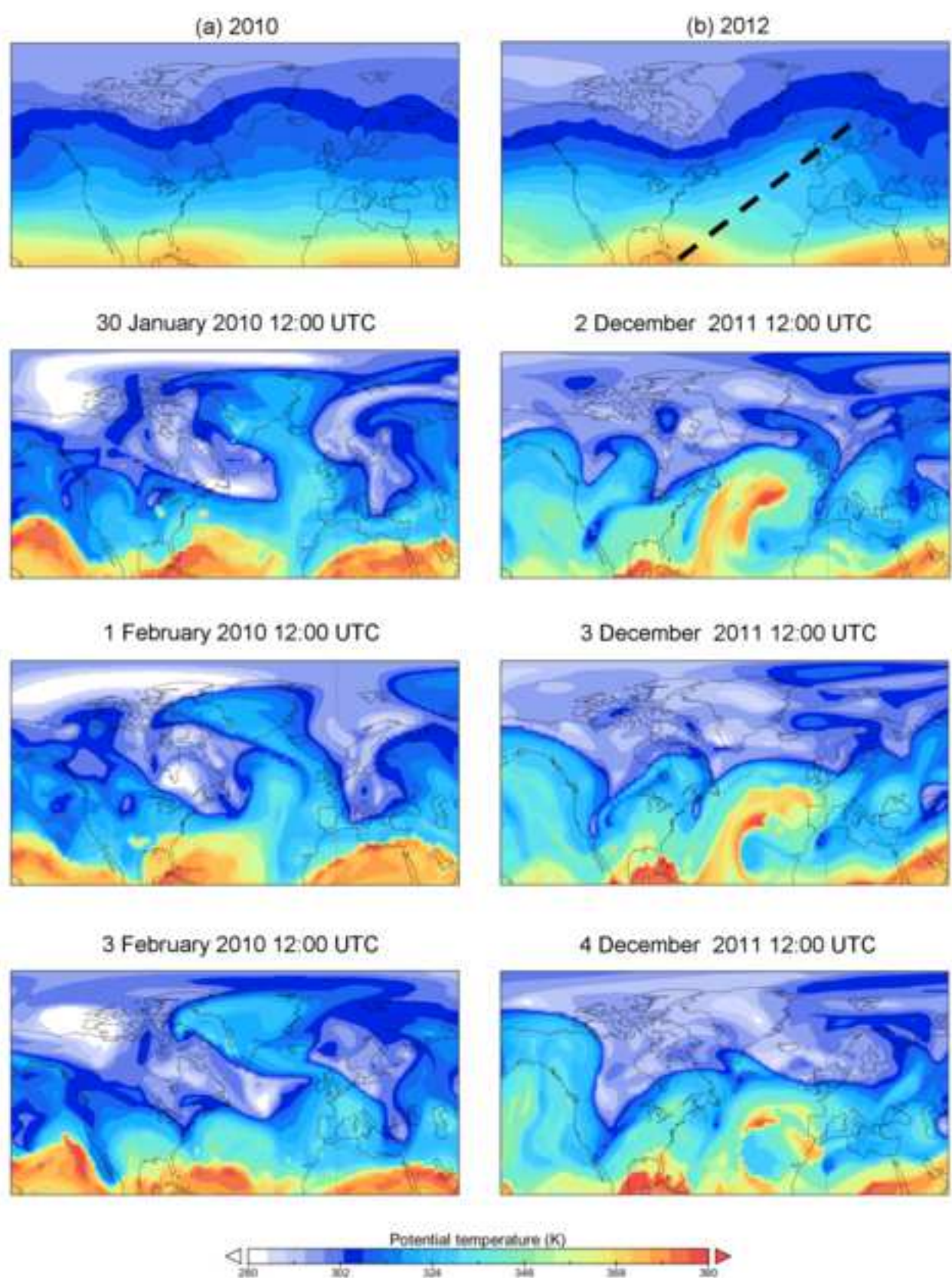


(d) 2012 anomalies



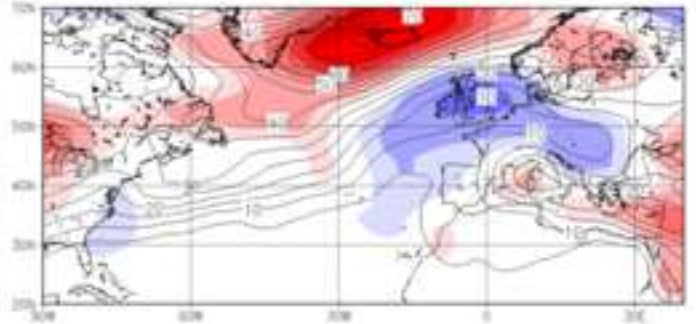
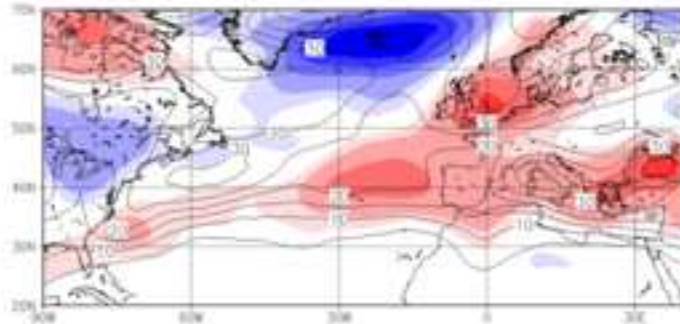
Blocking frequency (%)



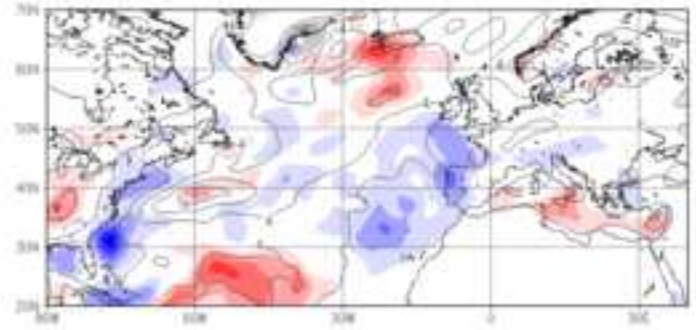
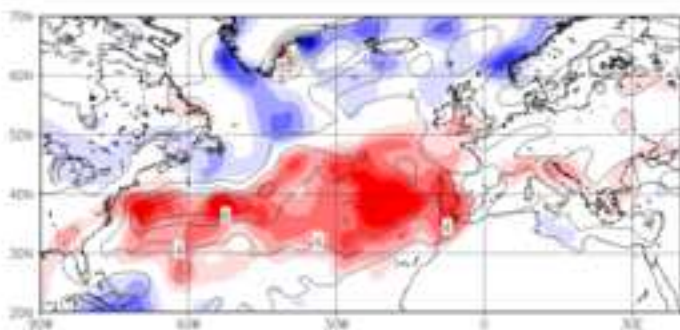


(a) 2010

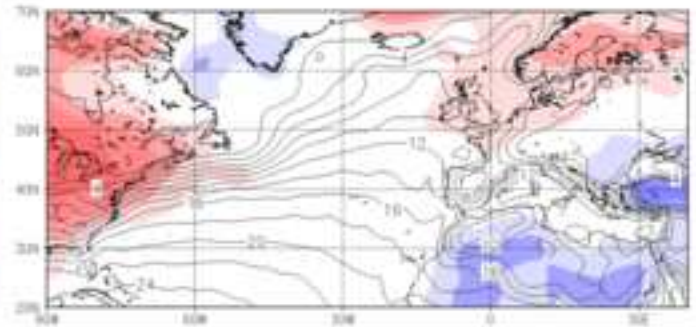
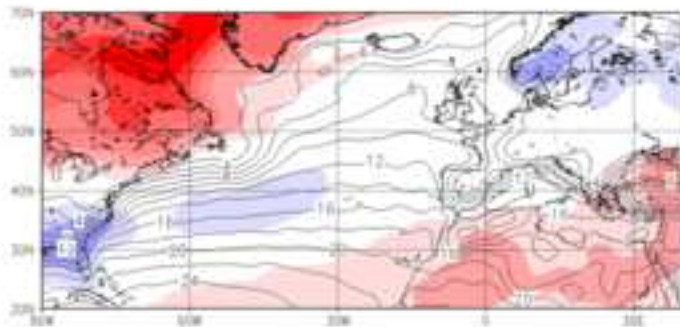
(b) 2012



Cyclone track density anomalies (days winter<sup>-1</sup> (%lat.)<sup>-2</sup>)

A horizontal color scale ranging from -20 (dark blue) to 20 (dark red), with intermediate values at -10, -5, -2.5, 2.5, 5, 10, and 15.

Precipitation rate anomalies (mm day<sup>-1</sup>)

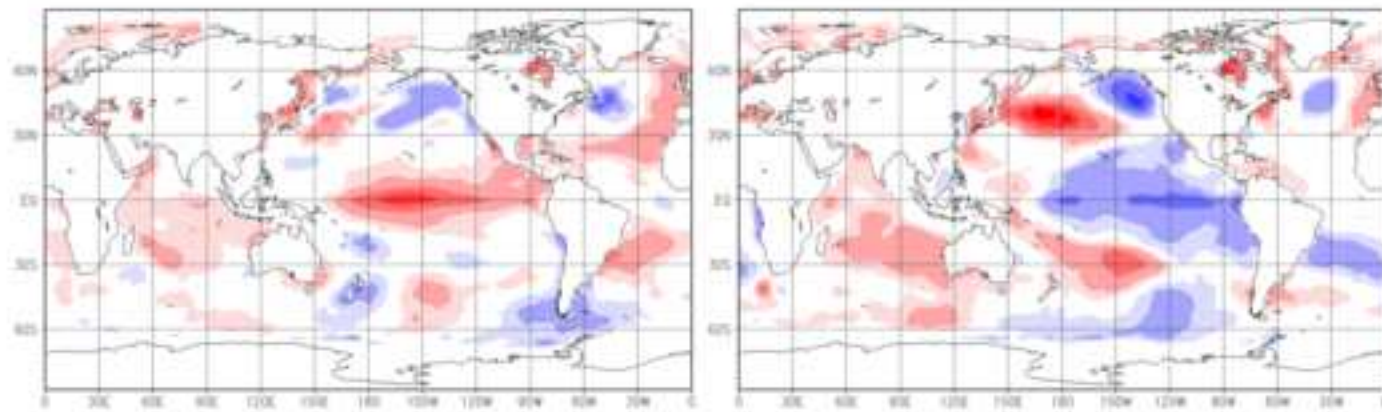
A horizontal color scale ranging from -2.5 (dark blue) to 2.5 (dark red), with intermediate values at -2, -1.5, -1, -0.5, 0.5, 1, 1.5, and 2.

2 m air temperature anomalies (°C)

A horizontal color scale ranging from -6 (dark blue) to 6 (dark red), with intermediate values at -5, -4, -3, -2, -1, 1, 2, 3, 4, and 5.

(a) 2010

(b) 2012

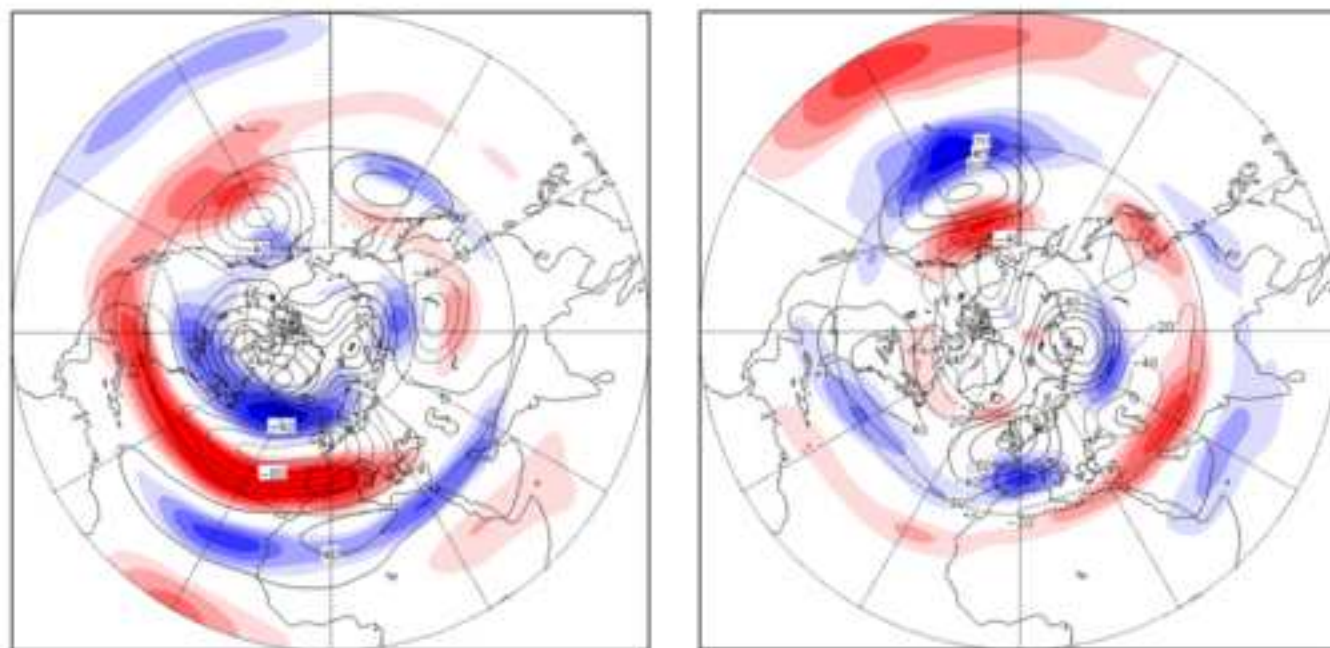


Sea surface temperature anomalies (Oct-Nov) (°C)



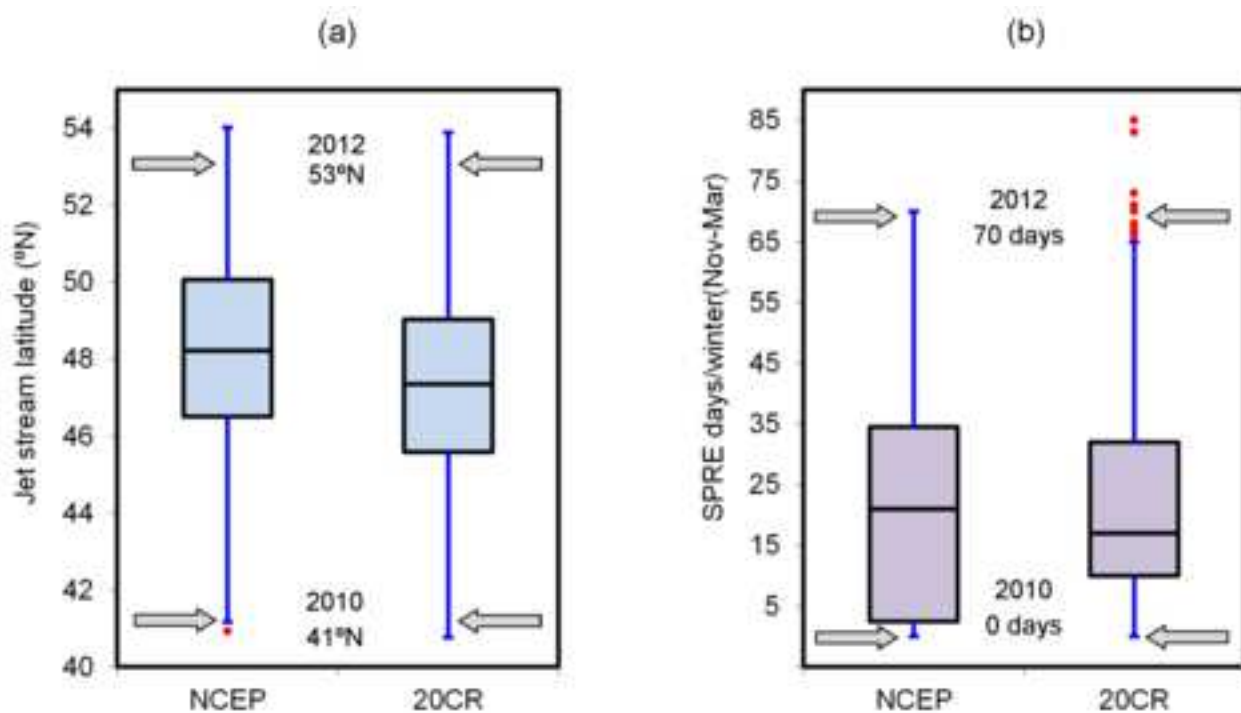
(c) 2010

(d) 2012



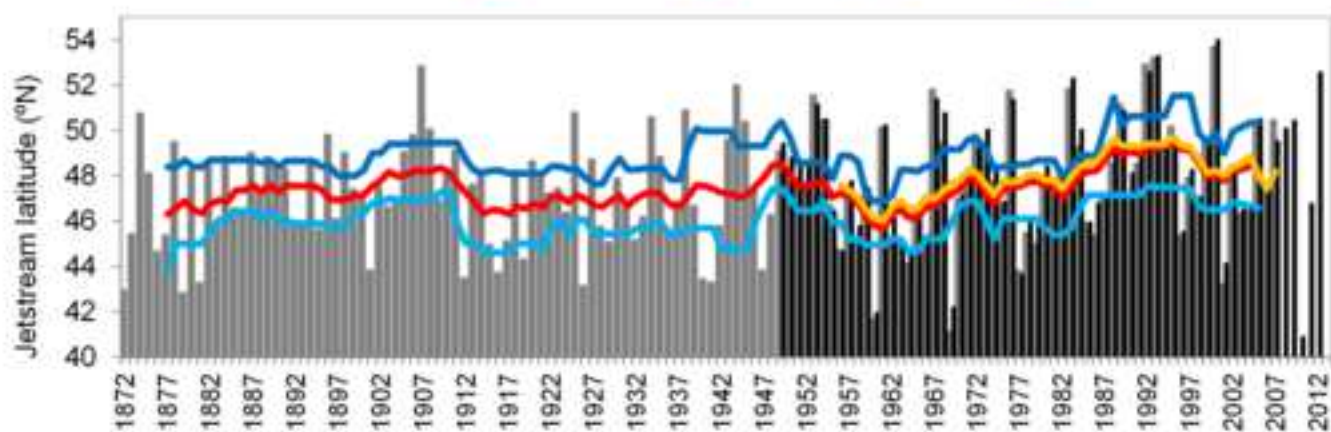
Zonal wind anomalies (Nov-Mar) ( $\text{m s}^{-1}$ )





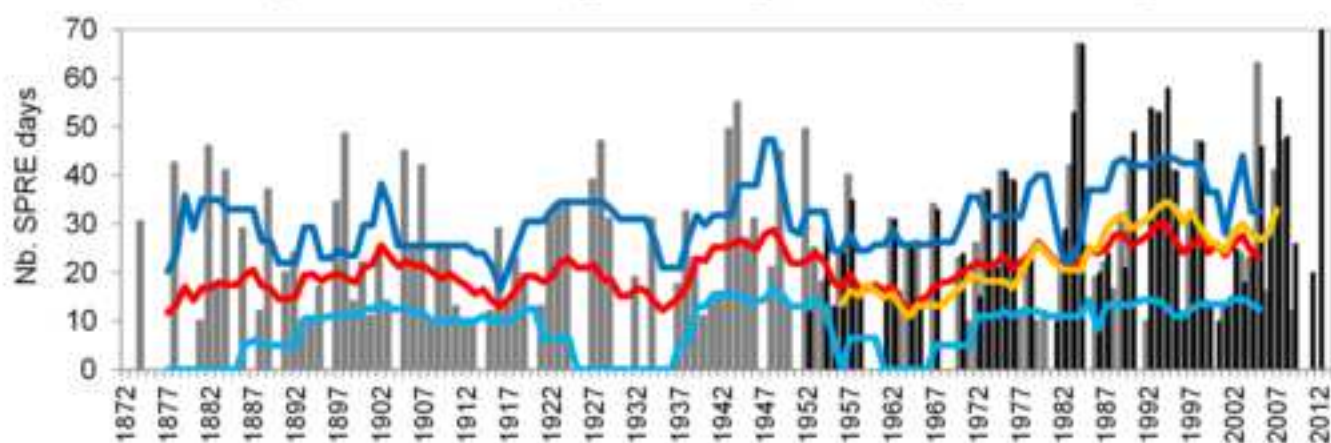
(c)

20CR\_P50  
  NN  
  Mean\_20CR  
  P25\_20CR  
  P75\_20CR  
  Mean\_NN



(d)

20CR\_P50  
  NN  
  Mean\_20CR  
  P25\_20CR  
  P75\_20CR  
  Mean\_NN



Supplemental Material

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