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1 **Anthropogenic climate change will intensify European explosive storms**
2 **analogous to Alex, Eunice, and Xynthia**

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10 ABSTRACT: Extratropical storms, particularly explosive storms or 'weather bombs' with ex-
11 ceptionally high deepening rates, present substantial risks and are susceptible to climate change.
12 Individual storms may exhibit a complex and hardly detectable response to human-driven climate
13 change because of the atmosphere's chaotic nature and variability at regional level. It is thus essen-
14 tial to understand changes in specific storms for building local resilience and advancing our overall
15 comprehension of storm trends. To address this challenge, this study compares analogues – storms
16 with a similar backward track until making landfall — in two climates of three explosive storms
17 impacting different European locations: Alex (October 2020), Eunice (January 2022), and Xynthia
18 (February 2010). We use a large ensemble dataset of 105 members from the Community Earth
19 System Model version 1 (CESM1). These analogues are identified in two periods: the present-day
20 climate (1991-2001) and a future climate scenario characterized by high anthropogenic greenhouse
21 gas emissions (RCP8.5, 2091-2101).

22 We evaluate future changes in the frequency of occurrence of the storms and intensity, as well as
23 on meteorological hazards and the underlying dynamics. For all storms, our analysis reveals an
24 increase in precipitation and wind severity over land associated with the explosive analogues in the
25 future climate. These findings underscore the potential consequences of explosive storms modified
26 by climate change and their subsequent hazards on various regions of Europe, offering evidence
27 that can be used to prepare and enhance adaptation processes.

28 SIGNIFICANCE STATEMENT: This study investigates the impact of climate change on ex-
29 plosive storms, or 'weather bombs,' and their potential consequences for European regions. We
30 project future scenarios of three specific storms, Alex, Eunice, and Xynthia, using a state-of-the-art
31 climate model. Our findings reveal an increase in precipitation and wind over land associated to
32 these storms, emphasizing the heightened risks associated with climate change. The significance
33 lies in understanding the local implications of explosive storms, aiding in the development of
34 resilient strategies and adaptation measures.

35 **1. Introduction**

36 Weather variability in the mid-latitudes is mainly controlled by atmospheric wave activity, con-
37 sisting of propagating synoptic-scale cyclonic and anticyclonic circulation. Therein, extratropical
38 storms play a key role in affecting the wave guide and producing the majority of high impact
39 weather (Wallace and Hobbs 2006). They contribute substantially to total precipitation (Hawcroft
40 et al. 2012) and are a source of wind energy (Liu et al. 2008; Rapella et al. 2023). Extratropical
41 storms can also exhibit extreme behaviour, being associated with strong precipitation and flooding
42 events (Hawcroft et al. 2018), strong and damaging winds (Roberts et al. 2014a), or a combination
43 of both (Owen et al. 2021). Given their potential to be associated with meteorological hazards
44 with significant socio-economic impacts (e.g., Liberato 2014; Jansa et al. 2001), understanding the
45 evolution of their characteristics in a future climate is crucial.

46 Several studies have assessed the role of climate change in modifying the underlying dynamics of
47 extratropical storms (e.g. Lehmann et al. 2014; Priestley and Catto 2022). Changes in frequency,
48 position and intensity of the storm tracks, namely the preferred regions where storms travel
49 through, are primary driven by changes in the horizontal temperature gradient in both lower and
50 upper troposphere and in the vertical temperature profile (Catto et al. 2019). The Coupled Model
51 Intercomparison Project (CMIP) phases 3, 5, and 6 generally agree on the spatial signature of
52 the projected changes in storminess in the North Atlantic (Harvey et al. 2020). Specifically,
53 models project a decrease in storm activity during summer, particularly in the southern regions,
54 and produce a tripolar pattern in winter of an increase in storm activity in the British Isles and
55 a decrease in the Mediterranean and Norwegian seas (Zappa et al. 2013; Priestley et al. 2020).
56 Regarding extreme storms, the response consist of a decrease in frequency of occurrence in the North

57 Atlantic basin, with a weak and local increase over the British Isles and the North Sea in winter
58 (Zappa et al. 2013; Seiler and Zwiers 2016). Sources of uncertainty of climate projections stem
59 from difficulties of isolating internal variability from the forced signal (Deser et al. 2012), as well
60 scenario and model uncertainty (Hawkins and Sutton 2009; Sansom et al. 2013). In addition, low
61 confidence still persists due to opposing thermodynamic processes that alter baroclinicity (Shaw
62 et al. 2016), and challenges in resolving meso-scale and small scale features such as the diabatic
63 processes (Schemm 2023).

64 While examining general trends in storm behaviour provides a fundamental understanding of the
65 potential hazards of climate change, it is essential to recognize that specific storms may exhibit
66 unique characteristics. This stems from the fact that specific storms are influenced by a combination
67 of factors that may not be accurately captured in general trends, giving rise to a chaotic nature in
68 the atmosphere and non-linear interactions. In addition, different regions may experience unique
69 environmental conditions, such as local topography or oceanic currents, resulting in variations in
70 atmospheric dynamics that influence the behavior of storms. Hence, our study aims to bridge
71 this gap by zooming in on the particular features of extreme storms in different regions. For this
72 reason, we employ an approach within the field of Extreme Event Attribution (EEA) (Trenberth
73 et al. 2015; Jézéquel et al. 2018), specifically designed to address these questions. This field
74 allows us to delve into the domain of weather science to understand the specific meteorological
75 conditions contributing to the event while simultaneously evaluating the role of climate change in
76 shaping its occurrence and intensity (Shepherd 2016). We use a recent EEA approach that involves
77 finding similar events, called *analogues*, in two different time periods and comparing their key
78 variables (Faranda et al. 2022). Some studies have adapted this methodology to be more targeted
79 for extratropical storms (Ginesta et al. 2022) as well as for Mediterranean storms (Faranda et al.
80 2023).

81 In our study, we further adapt this EEA approach for the analysis of explosive storms. Explosive
82 storms are characterized by a strong deepening rate in a short time period, and can produce
83 widespread damage when they make landfall (Liberato et al. 2013; Fink et al. 2009). These storms
84 were identified by Sanders and Gyakum (1980) as storms with a "Normalized central Deepening
85 Rate" (NDR_c) greater than 1:

$$NDR_c = \frac{DR_{24h} \sin(60^\circ)}{24h \sin(\varphi)}, \quad (1)$$

86 where DR_{24h} is the pressure difference over 24 hours measured at the storm center and φ is the
87 latitude at its second time step. This definition has been challenged, especially for the Southern
88 Hemisphere (Lim and Simmonds 2002; Allen et al. 2010), due to the fact that it may capture storms
89 moving rapidly towards an area of climatologically lower pressure rather than storms deepening
90 rapidly (Sinclair 1995). However, we use the historical definition by Sanders and Gyakum (1980),
91 as our aim is to compare storms based on their similar development and pressure change rather
92 than to assess the sensitivity of the explosive criterion.

93 Explosive storms, also known as "weather bombs", are mainly formed in regions of enhanced
94 baroclinicity (Roebber 1984). In the North Atlantic, they primarily form during the boreal winter
95 in the western part of the basin, where there is a strong horizontal temperature gradient linked to
96 the Gulf Stream and land-sea contrast, large moisture availability and strong vertical wind shear
97 (Reale et al. 2019; Brayshaw et al. 2009).

98 We focus on three explosive storms that hit different parts of Europe: Alex in October 2020,
99 Eunice in January 2022, and Xynthia in February 2010. Unlike many EEA studies that compare
100 the present climate with a pre-industrial climate (factual and counterfactual periods), our method
101 uses present and future climate projections with the Community Earth System Model version 1
102 (CESM1). Our study aims to:

- 103 1. Evaluate how well CESM1 simulates storms with development stages similar to the three
104 targeted storms.
- 105 2. Analyze changes in the frequency of these storms and their deepening rates in a future climate
106 scenario, considering the scenario with the highest greenhouse gases emissions, that is, the
107 Representative Concentration Pathway 8.5 (RCP8.5).
- 108 3. Examine changes in hazards of these events, quantified by measuring precipitation and wind
109 speed.
- 110 4. Characterize the underlying dynamics contributing to these observed changes.

111 In the subsequent sections, we present the characteristics of the storms (Section 2), describe the
112 data and methods used (Section 3), evaluate the model performance in simulating explosive storms
113 (Section 4), analyze changes in frequency and intensity of storms (Section 5), and assess changes
114 in climate drivers and underlying dynamics (Section 6). The conclusions of our study are presented
115 in section 7.

116 **2. Storm characteristics**

117 In this section we contextualize the three storms and provide an overview of the associated
118 impacts and meteorological drivers.

119 *a. Storm Alex*

120 Storm Alex occurred in early October 2020 and produced a devastating flood in the Alps region
121 in 24 hours. Alex caused record-breaking precipitation and hurricane-force winds in France and
122 Italy, resulting in at least 15 fatalities and over 2.5 billion euros in economic losses (WMO 2020;
123 European State of the Climate 2020; Météo France 2020; Aon 2020). Notable events included 630
124 mm of rain in Sambughetto and winds reaching 186 km/h in Belle-Île - Le Talut (European State
125 of the Climate 2020; Météo France 2020). The storm developed as a secondary cyclogenesis, that
126 is, as a frontal-wave instability along of a synoptic front of a pre-existing storm. It deepened rapidly,
127 enhanced by high upper level potential vorticity. The pressure dropped more than 30 hPa in the
128 first 24 hPa. It made landfall early 2 October with a minimum pressure of around 970 hPa. On
129 its southern flank, the strong pressure gradient favoured high quantities of water vapour transport,
130 and an atmospheric river was formed from the subtropical western North Atlantic to the vicinity
131 of the storm core (Davolio et al. 2022). In an EEA study based on reanalysis data (Ginesta et al.
132 2022), the persistence of the storm, as well as the accumulated daily precipitation, increased in the
133 present climate when compared to the recent past climate.

134 *b. Storm Eunice*

135 Eunice was the second and strongest storm of a cluster of winter storms (Met Office 2022)
136 that lasted between the 16th – 20th of February 2022 and mainly affected western Europe. The
137 storm, also known as Storm Zeynep or Storm Nora in Germany and Denmark, respectively, caused

138 widespread damage, 17 fatalities, and insured losses estimated at 2.5–3.5 billion euros (NL Times
139 2022; Anadolu Agency 2022; Deutsche Welle 2022; BBC 2022; RTL Info 2022; The Irish Times
140 2022; RMS 2022). Eunice formed from secondary cyclogenesis on February 17 in the North
141 Atlantic. It experienced explosive cyclogenesis with a central pressure drop of 30 hPa in 18 hours.
142 On February 18 at around 6 am Eunice made landfall in Ireland and then crossed the UK in 12
143 hours. A wind gust of 196 km/h was recorded in The Needles, Isle of Wight, the strongest ever
144 recorded in England. On February 18 at around 6 pm the storm was located over the North Sea
145 reaching a sea level pressure in its core below 970 hPa, the minimum of its lifetime. In the hours
146 that followed, the storm swept across Western Europe with force, hitting in particular Germany,
147 the Netherlands, and Belgium.

148 *c. Storm Xynthia*

149 In winter 2009/2010, the general atmospheric circulation over Europe was characterized by an
150 extreme and record-persistent negative phase of the North-Atlantic Oscillation (NAO) (Cattiaux
151 et al. 2010). This led to a low latitudinal position of the jet stream, several severe cold spells,
152 cold weather conditions and destructive storms. Xynthia, the strongest and most damaging storm
153 to hit Europe in that winter, occurred in late February/early March 2010, and raised interest in
154 the scientific community due to its uncommon meteorological characteristics (e.g. Liberato et al.
155 2013) and impacts (e.g. Chadenas et al. 2014; Vinet et al. 2012). It followed an unusual SW-NE
156 path, causing significant impacts in several western European countries, including more than 60
157 fatalities and insured losses of 1.5–3 billion euros (García-Pereda (NWC SAF/AEMET) 2010;
158 Kolen et al. 2013; Worlwide 2010; Chauveau et al. 2011). Unlike most extratropical storms that
159 intensify rapidly when they cross the polar jet stream (Uccellini 1990), Xynthia’s intensification
160 was primarily driven by the advection of low-level warm, humid air and associated with high
161 values of equivalent potential temperature (θ_e) (Fink et al. 2012). The storm underwent explosive
162 cyclogenesis between the 26th and the 27th while rapidly approaching to the Iberian Peninsula.
163 On the 27th at 18:00 UTC it reached its minimum sea level pressure below 970 hPa west of the
164 Bay of Biscay. It then swept across western France, resulting in a powerful storm surge that
165 locally exceeded 1.5 m and that produced most of the damages in France (Bertin et al. 2012).

166 Xynthia continued its path northeastwards hitting specially Belgium, the Netherlands, Germany
167 and Denmark.

168 **3. Datasets and methods**

169 *a. Datasets*

170 To address the above objectives, we use the Community Earth System Model version 1 (CESM1;
171 Hurrell et al. (2013)), which is a global coupled climate model with a horizontal resolution of
172 about 1 degree. The radiative forcing applied in all simulations is the historical forcing until
173 2005 and the Representative Concentration Pathway 8.5 (RCP8.5) forcing from the CMIP5 project
174 (Meinshausen et al. 2011) from 2005 onwards. We use a multimember initial condition ensemble
175 CESM-LE (CESM-LE; Kay et al. (2015)), consisting of a 35-member ensemble of simulations
176 from 1 January 1920 to 2100. To increase the number of members, two additional ensembles of
177 35 members each are performed. In both ensembles, 35 members are rerun from perturbations of
178 $O(10^{-13})$ on the initial atmospheric temperature field of the first member of the CESM-LE, starting
179 at 1980 and at 2081 (Röthlisberger et al. 2020). After a few years, due to the chaotic nature of
180 the climate system, the members are in distinct states of their internal variability, and thus they are
181 considered to be independent (Fischer et al. 2013). Hence, the experimental set-up of this study
182 consists of 1050 years of a *present* climate, from 1991 to 2000, and 1050 years of a *future* climate,
183 from 2091 to 2100. The radiative forcing is assumed to be relatively constant in a 10-year period.
184 Kay et al. (2015) showed that the spread of the CESM-LE due to internal variability is comparable
185 to CMIP5. In contrast to many CMIP5 models, CESM does not depict a too zonally oriented North
186 Atlantic storm track (Dolores-Tesillos et al. 2022). According to Dolores-Tesillos et al. (2022), the
187 model is able to reproduce fairly well storm frequencies and lifetimes, and most of the biases are
188 associated to weak or short living storms. They found an underestimation of the number of storms
189 over the ocean, of around -0.8 storms per month. At smaller scales, the model is able to represent
190 the properties and structure of extratropical storms and their associated warm conveyor belts (Joos
191 et al. 2023; Binder et al. 2023). The deepening rates of the weak and medium-strong storms in the
192 NH in winter are also well captured by the model but there is an underestimation of the explosive
193 ones (Binder et al. 2023).

194 In this study we also use ERA5 reanalysis data (Hersbach et al. 2020), covering the period from
 195 1950 to 2020, as a validation of the CESM model performance. The ERA5 dataset has a horizontal
 196 resolution of 31 km.

197 We use 6-hourly sea level pressure (SLP) to find the analogues, and we assess the meteorological
 198 hazards using 6-hourly precipitation rate (PR), and wind speed at 10m. We define a wind severity
 199 ratio (WSR_{90}) as the ratio between the maximum wind speed within a 24-hour period centered on
 200 the minimum sea level pressure stage of the storms, divided by the 90th percentile of wind speed
 201 for the entire period ($WSR_{90} = v_t/v_{90}$). The 90th percentile for ERA5 has been computed using
 202 the entire period, while for CESM, it has been computed based on the present period.

203 To better assess the drivers of the changes in SLP, PR, and WSR_{90} between CESM present and
 204 future periods we further analyze the following 6-hourly variables: equivalent potential temperature
 205 (θ_e) at 850hPa, horizontal gradient of θ_e ($\nabla\theta_e$) at 850hPa, distribution of the upper-tropospheric jet
 206 stream, and the low-level Eady Growth Rate (EGR) between 850hPa and 500hPa. The distribution
 207 of the upper-tropospheric jet stream is based on the methodology outlined in Koch et al. (2006),
 208 where jet occurrence is identified by averaging wind speeds between 400 hPa and 100 hPa (to
 209 account for height variations) and exceeding a threshold of 30 m/s. EGR is computed as:

$$EGR = 0.31 \frac{f}{N} \sqrt{\frac{\delta(u,v)}{\delta z}} \quad (2)$$

210 where $f = 2\Omega \sin \phi$ is the Coriolis parameter, $N = \sqrt{\frac{g}{\theta} \frac{\delta\theta}{\delta z}}$ is the Brunt-Väisälä frequency, and
 211 $\sqrt{\frac{\delta(u,v)}{\delta z}}$ is the vertical wind shear. Ω is the angular velocity of the Earth ($7.29 \times 10^{-5} rad/s$), ϕ
 212 latitude, u and v zonal and meridional wind speeds, θ potential temperature, and z geopotential
 213 height.

214 *b. Methods*

215 We use the method of analogues (Yiou 2014), which has already been applied to the study of
 216 extratropical storms (Ginesta et al. 2022; Faranda et al. 2023), to find similar storms to Alex,
 217 Eunice, and Xynthia. In the context of this study, an analogue is defined as a storm with a similar
 218 development stage or a comparable track during its evolution, which is explosive if the NDR_c is
 219 higher than 1 according to equation (1). The full tracks of storms Alex, Eunice, and Xynthia are

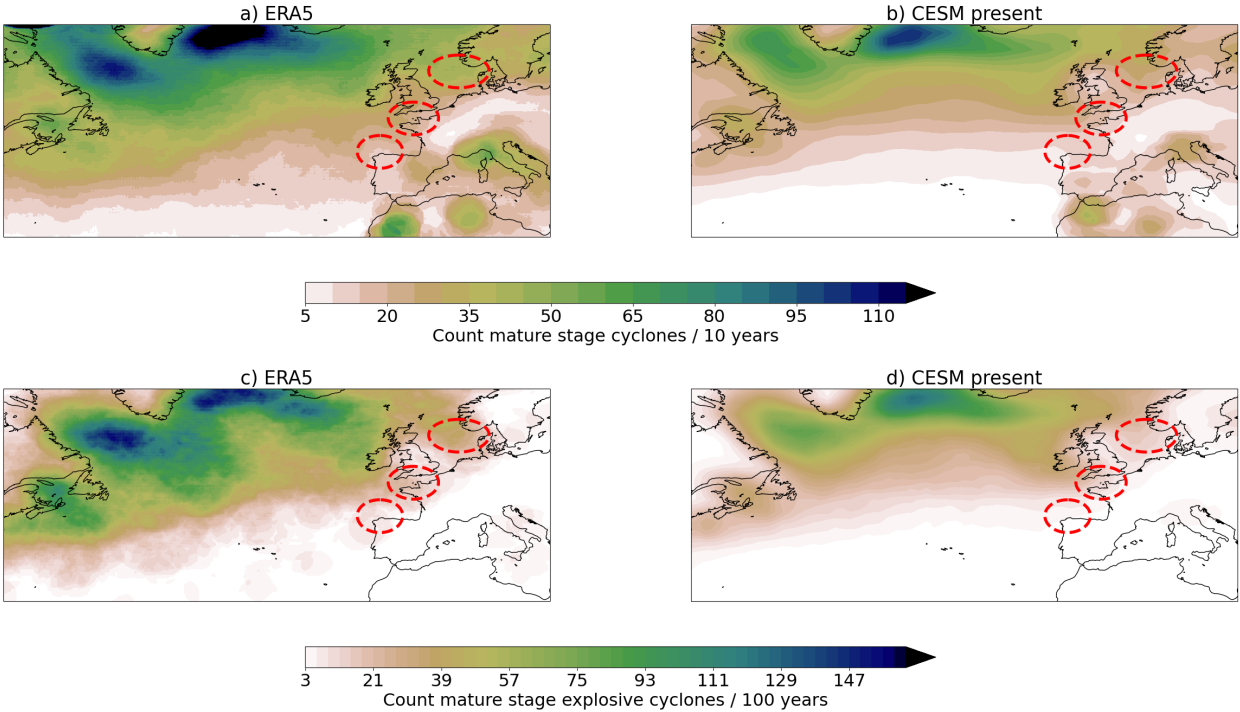
220 shown in figure A2 in the Appendix. We define the development stage of the storms as the 24h
221 period before reaching their mature stage (figure A2 of the Appendix from points 0 to 1). First,
222 we identify and track all storms in each dataset (ERA5, CESM present, CESM future). We use a
223 Lagrangian approach where storms centers are defined and tracked as local minima in the sea-level
224 pressure field (Wernli and Schwierz 2006). We then select the storms that have the most similar
225 development stages to the targeted storms based on our definition of analogue. For that, we apply
226 a two-step process:

- 227 • We first select all storms in the database that have a minimum sea level pressure lower than
228 1000 hPa and located within a circle of radius 300 km of the targeted storm center in its
229 minimum sea level pressure point. This filter ensures that only storms in their mature stage
230 are considered and that they have reached their minimum sea level pressure in the vicinity of
231 the targeted storm's center region. We refer to these storms as *mature stage* storms, and the
232 time when they reach their minimum sea level pressure is defined as *time 0*.
- 233 • We select the last five grid points of the development stage of the mature stage storms. As
234 we use 6-hourly data, this corresponds to the tracks 24 hours before the time 0 dates. For
235 each mature stage storm, we compute the averaged Euclidean distance between the track of
236 the storm and the track of the targeted storm. We select the 20% mature stage storms with the
237 lowest Euclidean distance from the targeted storm. This corresponds to the 20% most similar
238 development stage tracks. We term these *analogues*. The decision to use 20% is a trade-off
239 between finding tracks that resemble those of the targeted storms and having a sufficiently large
240 sample size to draw meaningful statistical conclusions. We tested that altering the percentage
241 to 10%, 15%, or 25% does not significantly impact our findings. We also select the analogues
242 that undergo explosive cyclogenesis, that is, that have a NDR_c greater than 1 (Eq. (1)). We
243 term these *explosive analogues*.

244 **4. Representation of explosive storms in CESM present-day climate**

245 Figure 1 shows the frequency of mature stage storms every 10 years for ERA5 (a) and CESM
246 present climate (b), as well as the frequency every 100 years of those that are explosive (c,d).
247 As noted by Dolores-Tesillos et al. (2022), there is an underestimation of storm numbers in the
248 model compared to observations, particularly evident in the ocean. Furthermore, we observe an

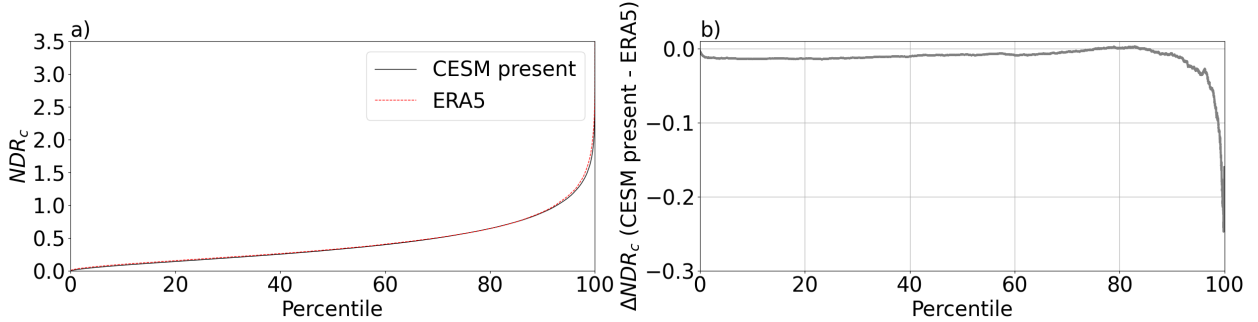
249 underestimation of mature stage storms west of Newfoundland, especially the explosive ones. In
 250 the regions studied, highlighted in red, we note a slight underestimation of both mature stage
 251 storms and explosive ones, especially in the North Sea. However, the bias is considerably smaller
 252 in these regions compared to the ocean. Despite the small proportion of storms assessed in this
 253 study compared to the overall North Atlantic basin, these three regions are highly susceptible to
 254 widespread damage when such storms make landfall, and the selected storms and their analogues
 255 represent a significant portion of weather bombs impacting these areas.



256 FIG. 1. Frequency of mature stage cyclones within 300 km for each grid point every 10 years for (a) ERA5 and
 257 (b) CESM present. (c,d) Frequency of those that are explosive, every 100 years. Red circles indicate the 300-km
 258 radius area used to identify analogues of the three storms.

259 Figure 2a shows the NDR_c of both ERA5 and CESM, similar as Binder et al. (2023) did for
 260 the Northern and Southern Hemispheres but focused on the North Atlantic. Figure 2b shows the
 261 differences between CESM present and ERA5. Consistent with their findings, we also identify a
 262 slight underestimation of the NDR_c of the most explosive storms in the basin, of up to around -0.2
 263 in the most extreme cases. However, there is strong agreement across almost all percentiles.

264 This comparative analysis, together with assessments by Dolores-Tesillos et al. (2022) and Binder
 265 et al. (2023), gives confidence in the model capability to simulate explosive storms making landfall
 266 on the western coast of Europe. Further exploration of the model ability to simulate analogues of
 267 the storms will be conducted in the subsequent section.



268 FIG. 2. a) Percentile curve of the Normalized central Deepening Rate (NDR_c) of storms in the North Atlantic
 269 for ERA5 and CESM present. b) Differences in the NDR_c between CESM present and ERA5.

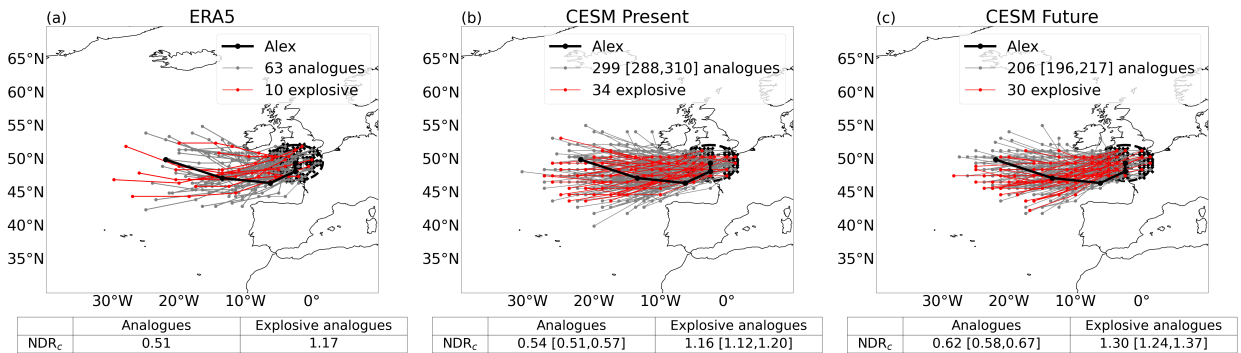
270 5. Changes in frequency and intensity

271 In this section, we first validate the CESM model performance in simulating analogue storms
 272 of Alex, Eunice, and Xynthia, using ERA5 reanalysis data. Then, we assess future changes in
 273 frequency of occurrence and intensity, measured by the NDR_c , by comparing CESM present and
 274 future climates.

275 a. Storm Alex

276 Figure 3 shows the tracks during the development stage of the analogues and explosive analogues
 277 of Alex for each dataset. The legends also display the number of analogues and explosive analogues.
 278 In the ERA5 70-year period, 63 analogues have been identified, that is, around 9 analogues every
 279 10 years. In contrast, fewer analogues are detected in the CESM present climate, with a frequency
 280 of almost 3 analogues every 10 years. This could be due to an underestimation of storm frequencies
 281 over the ocean (Dolores-Tesillos et al. 2022). In the ERA5 dataset, 10 of the 63 analogues are
 282 explosive, corresponding to a relative frequency of around 16% of the analogues. Three of these
 283 explosive analogues are known storms that made landfall in France (Table A1). The fraction of
 284 analogues that are explosive in the CESM present period is slightly lower than that of ERA5 (34

285 explosive analogues out of 299 analogues, that is, around 11%). The NDR_c , used here as a measure
 286 of the intensity, of the analogues and explosive analogues in CESM present is comparable to that
 287 of ERA5. We further measure the similarity of the analogues to the storm by computing the mean
 288 Euclidean distance between the 24-hour development stage tracks of the analogues and storm Alex.
 289 We term this *analogues quality* (Figs. 4a,c). The analogues quality distributions of CESM present
 290 show comparable values with ERA5, as no analogue was more than 500 km apart and most of them
 291 differed by around 380 km. These distributions indicate the model ability to simulate storms with
 292 development stage similar to Alex's. Figures 4b,d show the number of analogues per season. Most
 293 of the analogues occur in autumn season in both ERA5 and CESM present. However, in ERA5 the
 294 second most preferred season is spring, while in CESM present is winter. Few analogues are also
 295 detected in summer in both, ERA5 and CESM present.



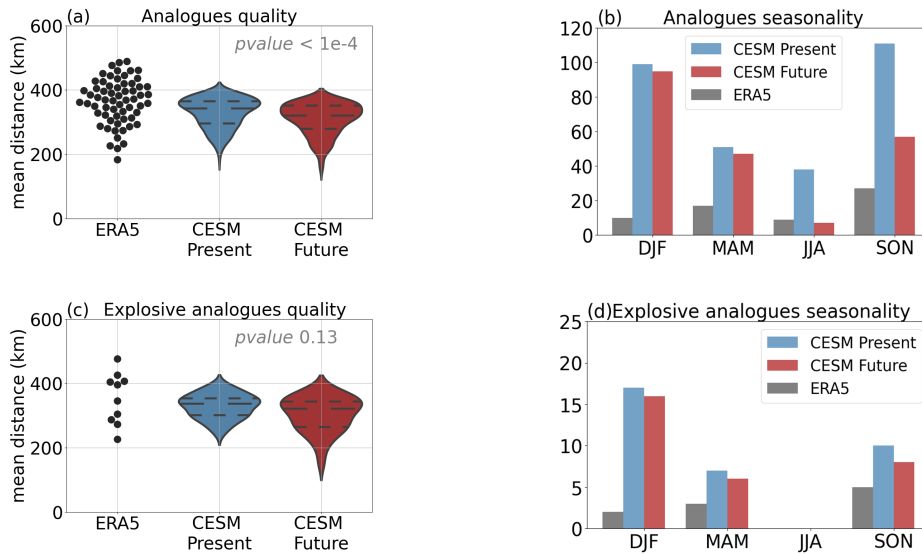
296 FIG. 3. 24-hour track of the development stage of storm **Alex** (thick black line) and its analogues (thin grey
 297 lines), for ERA5 (a), CESM present (b), and CESM future (c). Explosive analogues' tracks are highlighted in
 298 red. The dashed-line circle indicates the 300-km area used to identify mature stage storms. The figure legend
 299 shows the number of analogues and explosive analogues. The tables beneath the figures depict the Normalized
 300 Deepening Rate (NDR_c) values, calculated using equation 1, for both analogues and explosive analogues. 95 %
 301 confidence intervals for CESM present and CESM future, determined using a bootstrap test in which ensemble
 302 members were resampled, are indicated in brackets. The NDR_c values are also shown in figure A1 as a boxplot
 303 distribution.

304 There is a statistically significant decrease in the number of analogues in the future climate with
 305 respect to the present from 299 to 206 (Fig. 3). This decrease is mainly seen in autumn and summer,
 306 but there is also a slight decrease in winter and spring (Fig. 4b). There is little change in the number

307 of explosive analogues (34 to 30) (Fig. 3), with a decrease in frequency mainly in autumn (Fig.
308 4d). The relative frequency of explosive storms increases from present to future periods from 11%
309 to 15%. However, this increase is comparable to the model bias, suggesting that while the model
310 can detect a significant climate change signal, uncertainties regarding its magnitude may arise due
311 to model biases. There is an increase in NDR_c of both analogues and explosive analogues in the
312 future climate with respect to the present, which is considered statistically significant because the
313 confidence intervals do not overlap. This suggests that the analogues and explosive analogues in
314 the future climate will be associated with more intense deepening rates. In addition, the analogues
315 travel larger distances during their development stage in the future period (not shown). Regarding
316 the quality of the analogues, there is a statistically significant increase in the future period with
317 respect to the present (Fig. 4a). This indicates that analogues in future conditions resemble better
318 Alex's development stage than in the present climate. In summary, anthropogenic radiative forcing
319 is reducing the number of analogues of Alex, specially in autumn, but increasing their similarity
320 to the storm as well as the deepening rates.

328 *b. Storm Eunice*

329 In ERA5 we found 126 analogues, that is, around 18 every 10 years (Fig. 5). However, CESM
330 again underestimates the number of analogues, detecting 6–7 every 10 years in the present climate
331 (696). 23 out of 126 analogues are explosive in the ERA5 dataset, of which 8 are documented storms
332 that had an impact in Europe (Table A1). This corresponds to a relative frequency of explosive
333 storms of 18.3%. The relative frequency of analogues that undergo explosive cyclogenesis in
334 the CESM present is half of that of ERA5 (9.6%). In addition, the NDR_c of the analogues and
335 explosive analogues is slightly lower in the model than in ERA5 for both present analogues and
336 explosive analogues. Regarding the quality of the analogues (Fig. 6a), the analogues detected
337 by the model have lower mean Euclidean distances than those detected by ERA5. This indicates
338 that the model is good at reproducing storms that resemble Eunice's development stage. In the
339 ERA5 dataset, most of the analogues are found in autumn, while winter and summer have a similar
340 frequency (Fig. 6b). In the CESM present, the number of analogues in winter is slightly higher
341 than than in autumn.



321 FIG. 4. (a,c) Mean Euclidean distances between the 24-hour track of the development stage of storm **Alex**
 322 and its **analogues** and explosive analogues for ERA5 (black dots), CESM present (blue probability distribution),
 323 and CESM future (red probability distribution). Dashed lines in violin plots show the quartiles 25%, 50%, and
 324 75%. A Kolmogorov-Smirnov test was used to determine the statistically significant difference between CESM
 325 present and future distributions, with the resulting p-value indicated in the figure. (b,d) Number of analogues per
 326 season: SON (September, October, November), DJF (December, January, February), JJA (June, July, August),
 327 and MAM (March, April, May).

342 Despite no significant changes in the number of analogues in the CESM future climate with
 343 respect to the present climate (Fig. 5b,c), there is a decrease in frequency in autumn, summer and
 344 spring, and an increase in winter (Fig. 6b). In the case of explosive storms, there is a significant
 345 increase in the number of explosive analogues (67 to 95), corresponding to an increase in the
 346 relative frequency of explosive cyclogenesis in a future climate. This increase is mainly seen in
 347 winter (Fig. 6d), and a decrease again in autumn. The NDR_c of the analogues increases in a future
 348 climate (Fig. 5b,c), but there are no significant changes in NDR_c of the explosive analogues. In
 349 the future climate, the analogues and explosive analogues quality is better than in the present, as
 350 evidenced by the statistically significant differences in probability distributions (Fig. 6a,c). As also
 351 seen in Figure 5, the spatial spread in the development stage tracks of the analogues is lower in the
 352 future climate, which means that future analogues represent Eunice's tracks better than those in
 353 the present. In summary, there is a significant increase in the frequency of explosive cyclogenesis

354 in the future climate in winter. Additionally, the quality of analogues and explosive analogues
 355 improves significantly in the future. These changes collectively suggest an increased likelihood of
 356 Eunice-type storms in the future climate in winter.

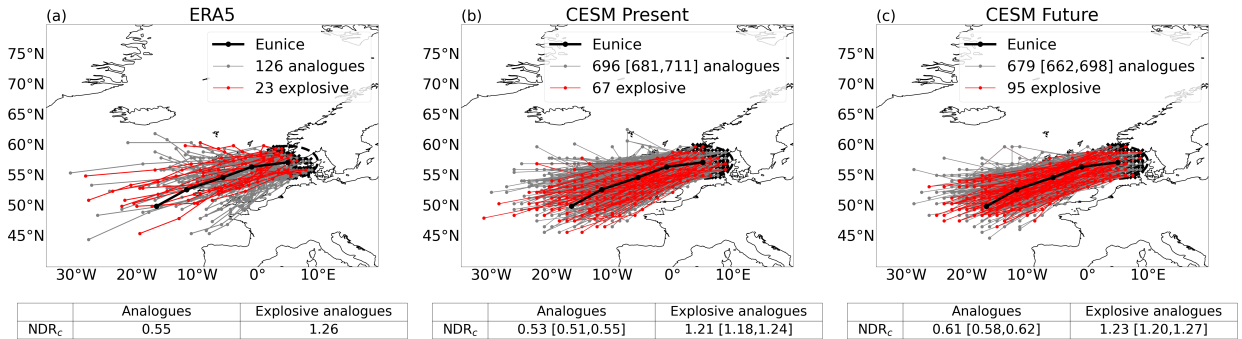


FIG. 5. Same as figure 3 but for storm **Eunice**.

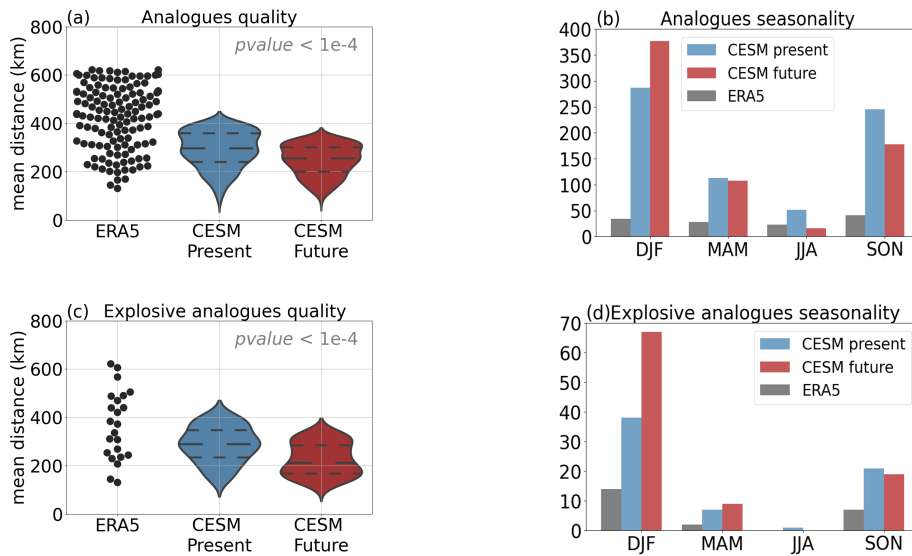


FIG. 6. Same as figure 4 but for storm **Eunice**.

357 *c. Storm Xynthia*

358 About 5 analogues every 10 years are detected in ERA5 and almost 1 every 10 years in the
 359 CESM present dataset (Fig. 7). This suggests that the CESM model underestimates the number
 360 of analogues that reach Galicia in their mature stage, linked to an underestimation of the storm
 361 frequency in that region shown by Dolores-Tesillos et al. (2022). In terms of explosive occurrence,
 362 3 out of 38 analogues underwent explosive cyclogenesis in ERA5 period, that is, around 8% of the

363 analogues. One of these is Miguel, a storm that affected western Europe in 2019 (Table A1). In
 364 the CESM present, the fraction of analogues that undergo explosive cyclogenesis is higher than in
 365 ERA5 (14 out of 101, that is, around 14%). In addition, the NDR_c of the analogues of the CESM
 366 present is higher than in ERA5. Despite the possible model biases, figures 8a,c show that the
 367 analogues and explosive analogues quality of the CESM dataset is comparable to that of the ERA5
 368 period. In ERA5 the analogues occur more often in autumn, while in the CESM present dataset it
 369 is in spring (Fig. 8b). In terms of the relative change between present and future climates, there
 370 is a significant decrease in the number of analogues in the future climate (101 to 68) (Fig. 7b,c).
 371 This decrease occur specially in spring, but also in autumn and summer (Fig. 8b). The number
 372 of explosive storms decreased slightly (from 14 to 11), with a decrease in spring and autumn but
 373 an increase in winter (Fig. 8d). Hence, there is an increase in the relative frequency of explosive
 374 storms, from around 14% to 16%. The NDR of the explosive analogues increases significantly
 375 under future climate conditions. However, due to the overlap in the confidence intervals, it is
 376 not possible to conclude that this increase is statistically significant, likely due to the insufficient
 377 sample size. No statistically significant changes are found in the analogues quality distributions
 378 between the two periods (Fig. 8a,c).

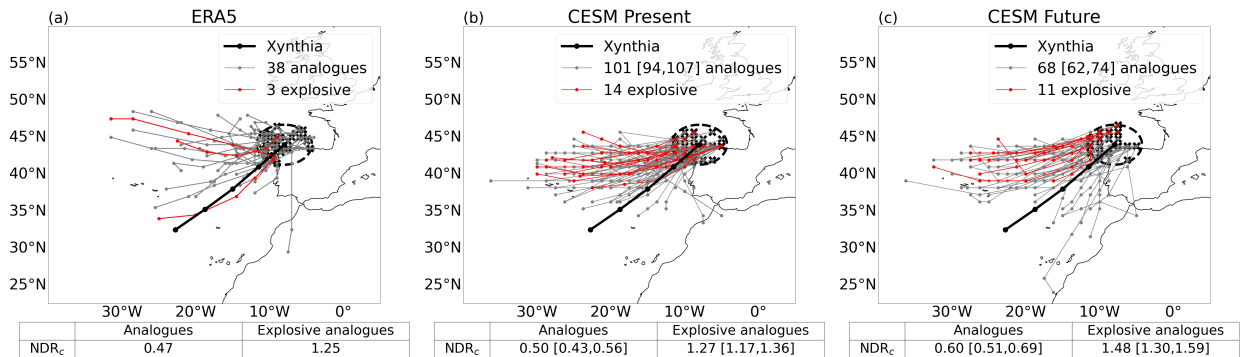


FIG. 7. Same as figure 3 but for storm **Xynthia**.

379 6. Meteorological hazards and Dynamics

380 In this section, we analyze changes in the fields of precipitation and wind severity ratio. To gain
 381 deeper insights into the evolving patterns of explosive analogues, we also assess the atmospheric
 382 dynamics contributing to these changes.

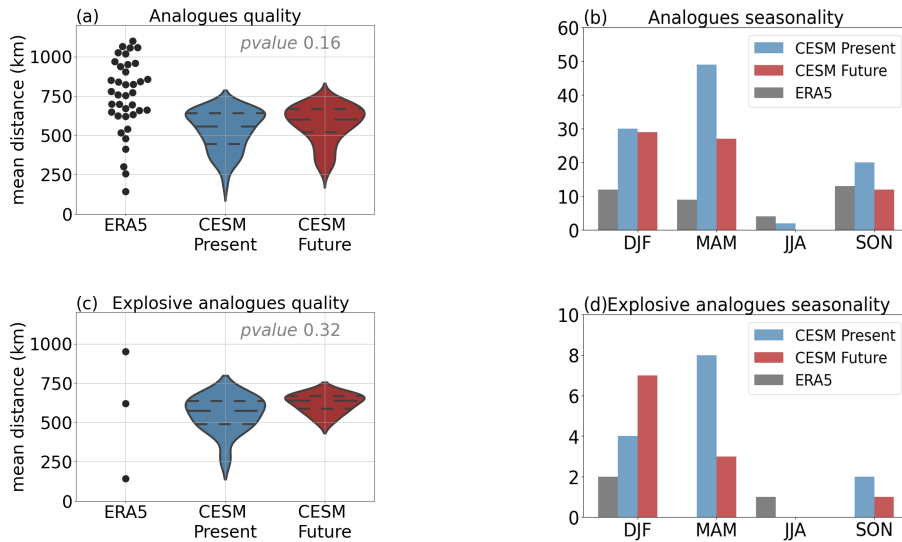


FIG. 8. Same as figure 4 but for storm **Xynthia**.

383 *a. Storm Alex*

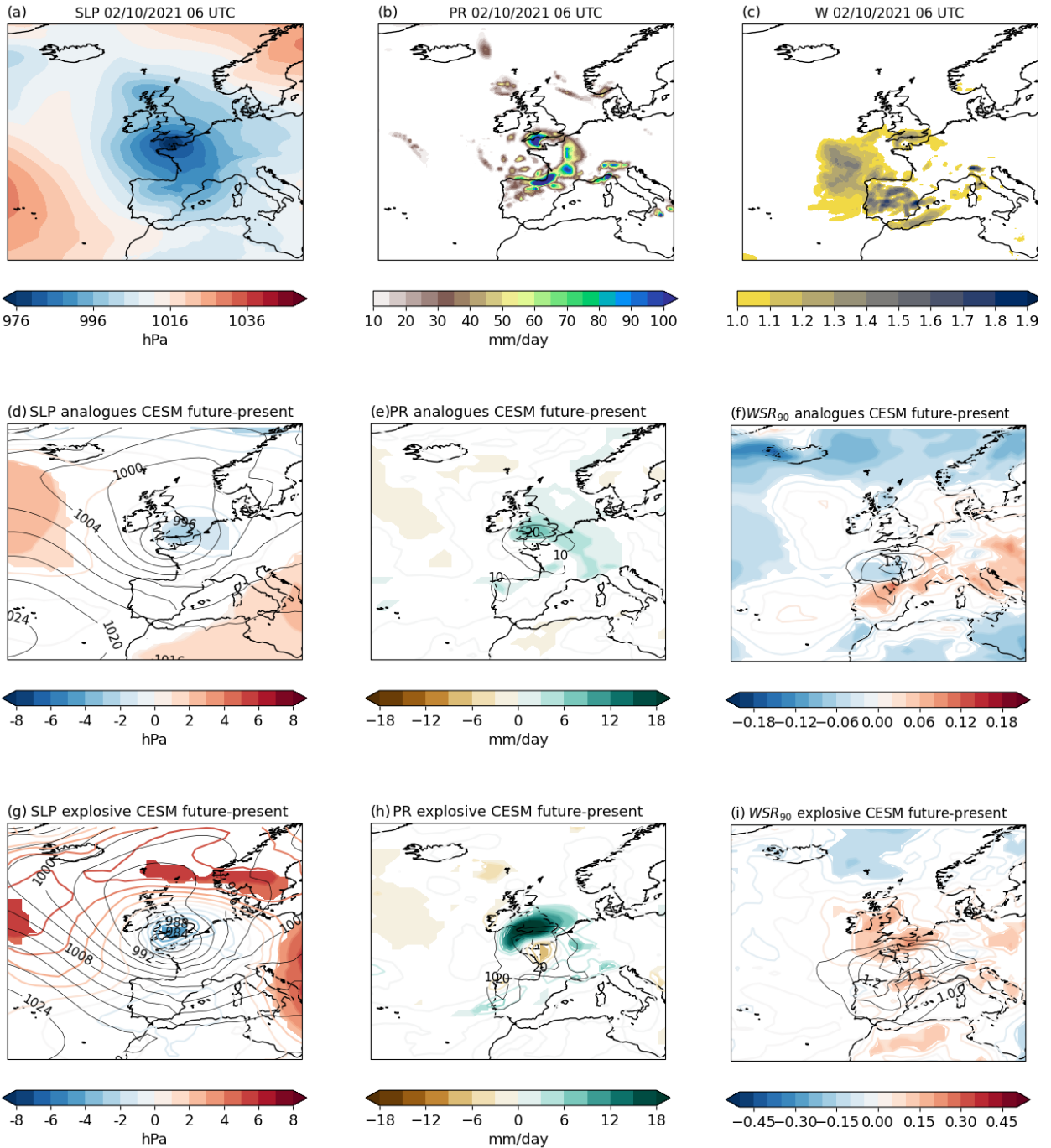
384 Figures 9a,b,c show the sea–level pressure (SLP), precipitation rate (PR), and wind severity ratio
 385 (WSR_{90}) fields of storm Alex using ERA5 data at its time 0 date. The minimum SLP is around
 386 970 hPa, and the storm center is squeezed over the English channel. Regarding PR, precipitation is
 387 primarily located along the storm’s frontal structure, as well as over the Southeastern France coast
 388 and windward of the Alps. High WSR_{90} is predominantly observed in the southwestern section
 389 of the storm. The CESM present composites of analogues and explosive analogues for SLP, PR
 390 and WSR_{90} are shown in black contours in figures 9d–i as well as in figure A3 in the Appendix.
 391 As expected, the pressure gradient in the explosive analogues composites is higher than that in
 392 the analogues (higher and closer number of black contours in Fig. 9g,d, respectively), resulting
 393 in lower SLP values in the storm core. In addition, explosive analogues are associated to higher
 394 PR and WSR_{90} (black contours in Fig. 9h,i, respectively) than those of the analogues (Fig. 9e,f,
 395 respectively). SLP composites of both CESM present analogues and explosive analogues (Fig.
 396 9d,g) depict a cyclonic structure with the center over the English channel, consistent with Alex.
 397 With respect to the PR pattern, this is predominantly located within the storm core and its southern
 398 region (Fig. 9e,h). Due to the lack of precise alignment of storm fronts among the analogues, the
 399 PR pattern does not display a clearly defined frontal area. High values of WSR_{90} are located in the
 400 center and southern flank of the storm (Fig. 9f,i).

401 Shading in figures (Fig. 9d–f) show differences CESM future – minus – present of the analogues
402 composites for SLP, PR, and WSR_{90} , respectively. The analogues in the future period show positive
403 anomalies of SLP northward of the Azores anticyclone as well as in the eastern Mediterranean (Fig.
404 9d). This contributes to increase the amplitude of the Rossby waves. In addition, there are SLP
405 negative anomalies in the core of the analogues. This means that the analogues in the future period
406 are associated to lower core pressures and to an increased pressure gradient. This, in turn, might be
407 linked to increase WSR_{90} in the future period in the southern flank and over land (Fig. 9f). Despite
408 a decrease in the center and northern flank, there is an overall increase in WSR_{90} associated with
409 the analogues. In addition, PR increases, specially to the east of the storm core, in the future period
410 (Fig. 9e). The SLP differences of the explosive analogues depict a similar structure to that of the
411 analogues (Fig. 9g), with deeper storms in the future period and positive anomalies on the eastern
412 Mediterranean and southern Scandinavia. This increase in the SLP gradient is also reflected by an
413 increase in WSR_{90} (Fig. 9i), which is particularly high over land, especially in the UK and western
414 France, Belgium, and the Netherlands. Figure 9h depicts an increase of PR in the northern flank
415 analogues' core and a decrease, albeit smaller, southward.

416 The PR and WSR_{90} patterns of extratropical storms such as Alex and its analogues are mostly
417 influenced by the position and intensity of weather fronts. To assess changes in the weather fronts,
418 we evaluate the equivalent potential temperature at 850 hPa pattern (θ_e , figures 10a,b). We also
419 compute the gradient of the θ_e field ($\nabla\theta_e$). The regions of the maximum $\nabla\theta_e$ are shown by
420 white dashed lines in figures 10a,b, typically characterizing the presence of weather fronts. Figure
421 10c illustrates the future minus present differences in $\nabla\theta_e$, providing insights into the changes in
422 front positions. In the CESM future, θ_e is overall higher than in the present, as a result of the
423 expected increase in global temperatures and water vapour content in a changing climate (shading
424 in Fig. 10a,b). Regarding the regions of maximum $\nabla\theta_e$ (white dashed line in Fig. 10a,b), we
425 interpret that a cold front originates southwestern France and extends towards north of the Azores,
426 as it is typically characterized by cold temperatures behind the warm sector. The other regions of
427 maximum $\nabla\theta_e$ are over English Channel extending towards central western Europe, and they would
428 be associated to the occluded and warm fronts, respectively. Regarding the future minus present
429 differences in $\nabla\theta_e$, we see a noticeable increase and a slight southward shift along the position of
430 the cold front (Fig. 10c). We also observe a northwestward shift in the warm front. These shifts

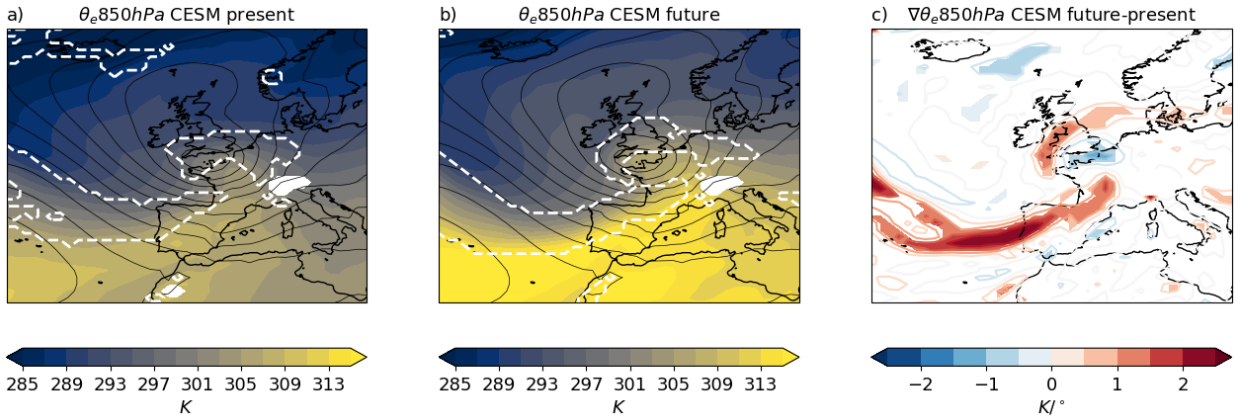
431 lead to a relocation of weather fronts of the explosive analogues in the future climate compared to
432 the present, potentially indicating a more rapid development of storms.

433 We also assess the upper-tropospheric jet stream distribution (Fig. 11) at the time 0 dates.
434 Figures 11a and b show that the jet stream is situated in the southern flank and slightly westward
435 of the low-level cyclone. Hence, the surface low is located at the left exit region of the jet streak.
436 This configuration is typical of storms at their maximum intensity. In the future period, there is
437 an extension and consequent intensification of the jet downstream and southward compared to the
438 present composites. This downstream intensification may be associated with stronger upper-level
439 divergence, an increase in ascent airflow, and consequently, an increase in storm intensity and
440 precipitation.



441 FIG. 9. (a) Sea level pressure (a), (b) precipitation rate, and (c) wind severity ratio *Alex* at time 0 using ERA5
 442 data. (d–i) Black contours: Composites of the CESM present **analogues** and **explosive analogues** of storm **Alex**
 443 at their *time 0* dates of (d,g) sea-level pressure, at 4 hPa intervals, (e,h) hourly mean precipitation rate, from
 444 10 mm/day and every 5 mm/day, and (f,i) hourly wind severity ratio, from 1.0 and every 0.1. Black contours
 445 are the same than shading in figure A3. Coloured contours: CESM future minus present differences of the
 446 composites of the analogues. Shading: CESM future minus present statistically significant differences, in which
 447 we bootstrapped the analogues of future and present periods. The null hypothesis of no difference is rejected if
 448 the absolute value of the difference exceeds the 95th percentile of the bootstrap distribution

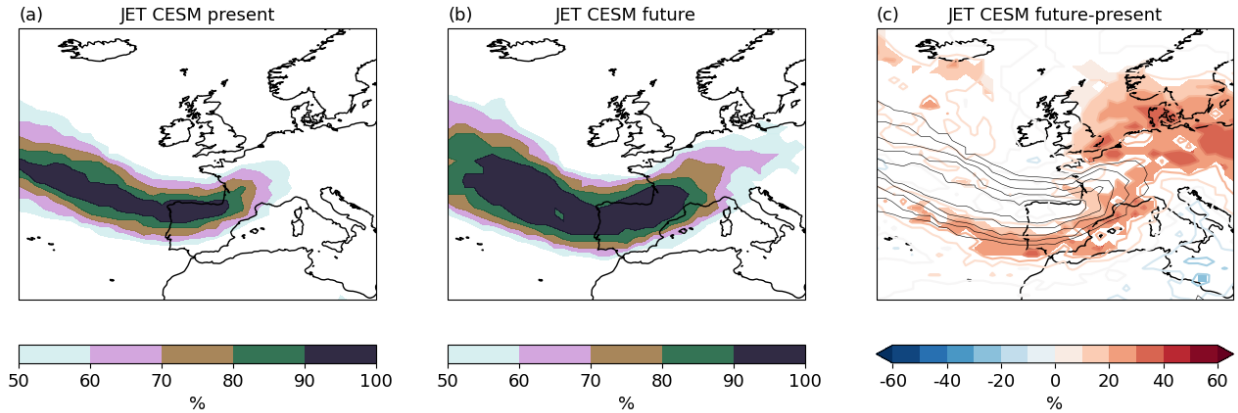
449 To further link changes in PR and WSR_{90} of explosive analogues with the dynamics and possible
 450 drivers, we assess the changes in eady growth rate (EGR, equation 2), convective precipitation
 451 (PRECC), and large-scale precipitation (PRECL). We observe a slight increase in EGR 24 hours
 452 prior to the mature stage of the storms, indicating an enhanced baroclinicity in future explosive
 453 analogues compared to the present (Fig. 12a). This could be linked to an increase in the NDR
 454 (Fig. 3b,c) and in the severity of storms in terms of wind speed (Fig. 9i). Furthermore, during
 455 the mature stage of the storms, we observe an overall increase in both PRECC and PRECL (Fig.
 456 12b,c). Notably, PRECL contributes the most to the spatial changes observed in total precipitation
 457 (Fig. 9h). These changes in the PRECL pattern might be linked with the cyclonic shift of the
 458 weather fronts seen in figure 10c and changes in the stratiform precipitation produced by the warm
 459 conveyor belt.



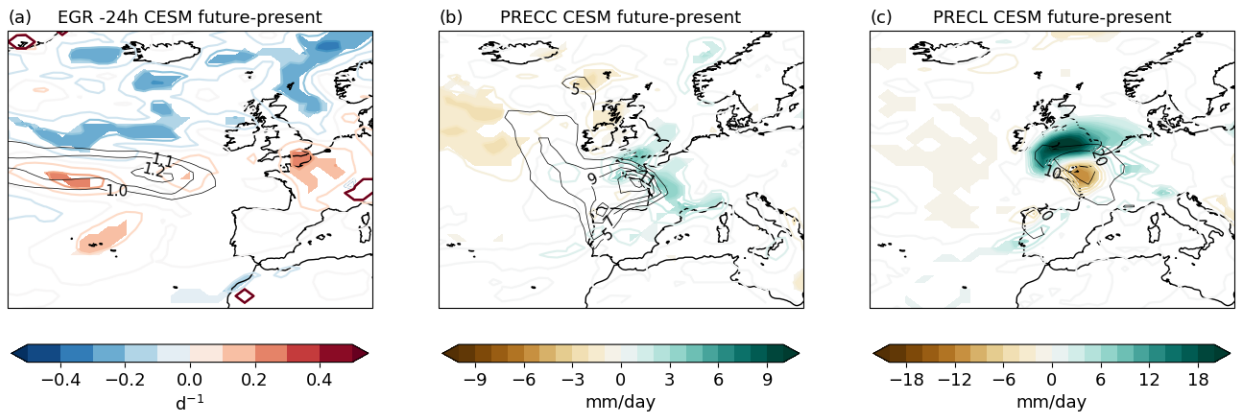
460 FIG. 10. (a,b) Shading: equivalent potential temperature at 850hPa for CESM (a) present and (b) future
 461 **explosive analogues of Alex** at their time 0 dates. White dashed lines: values exceeding the 80th percentile of
 462 the equivalent potential temperature gradient at 850 hPa. Black contours: composites of SLP at 4 hPa intervals
 463 (same as the shading in figure A3). (c) CESM future minus present differences in the composites of the horizontal
 464 gradient of equivalent potential temperature at 850 hPa.

472 *b. Storm Eunice*

473 Storm Eunice was situated over the North Sea during its mature stage (Fig. 13a). At that time,
 474 precipitation was relatively modest along a frontal line (Fig. 13b), while wind speeds were notably
 475 high, especially on the southern flank of the storm and over land (Fig. 13c). The composites of



465 FIG. 11. Distribution of the jet events for CESM (a) present and (b) future **explosive analogues** of **Alex** at their
 466 time 0 dates. (c) Shading: CESM future minus present differences in the distribution of the jet events. Black
 467 contours: CESM present composite of the distribution of the jet events.



468 FIG. 12. Shading: CESM future minus present differences in the composites of **explosive analogues** of
 469 (a) Eady growth rate 24 hours before the time 0 dates (EGR), (b) convective precipitation (PRECC), and (c)
 470 large-scale precipitation (PRECL), respectively. Black contours: composites of CESM present of EGR, PRECC
 471 and PRECL (shadings in Figures A4).

476 analogues and explosive analogues exhibit similar patterns of SLP, represented by black contours
 477 in figure 13d,g, respectively, and shading in figure A5a, d. In addition, the positions of highest PR
 478 and WSR_{90} in both analogues and explosive analogues (A5e,f and A5h,i) coincide with those of
 479 storm Eunice. Explosive analogues show, as expected, lower pressure at their core, and higher PR
 480 and WSR_{90} than the analogues.

481 The SLP pattern of the future analogues depicts lower pressures in the cyclonic structure and
482 higher pressures in the anticyclonic with respect to the present analogues (Fig. 13d). This is linked
483 to deeper analogues as well as an increase in the SLP gradient in their southern flank. The PR
484 pattern depicts an increase downstream of the analogues center and extended in western Europe
485 (Fig. 13e), potentially linked to an increase in the uplift of moist air in the warm conveyor belt
486 associated with lower pressure cores. In terms of WSR_{90} , there is also an increase in the southern
487 and eastern part of the analogues over land (Fig. 13f), which corresponds to the warm sector. The
488 differences in the patterns of explosive analogues depict a similar pattern than the analogues: lower
489 SLP, increase in PR, and stronger WSR_{90} specially over land (Fig. 13g,h,i).

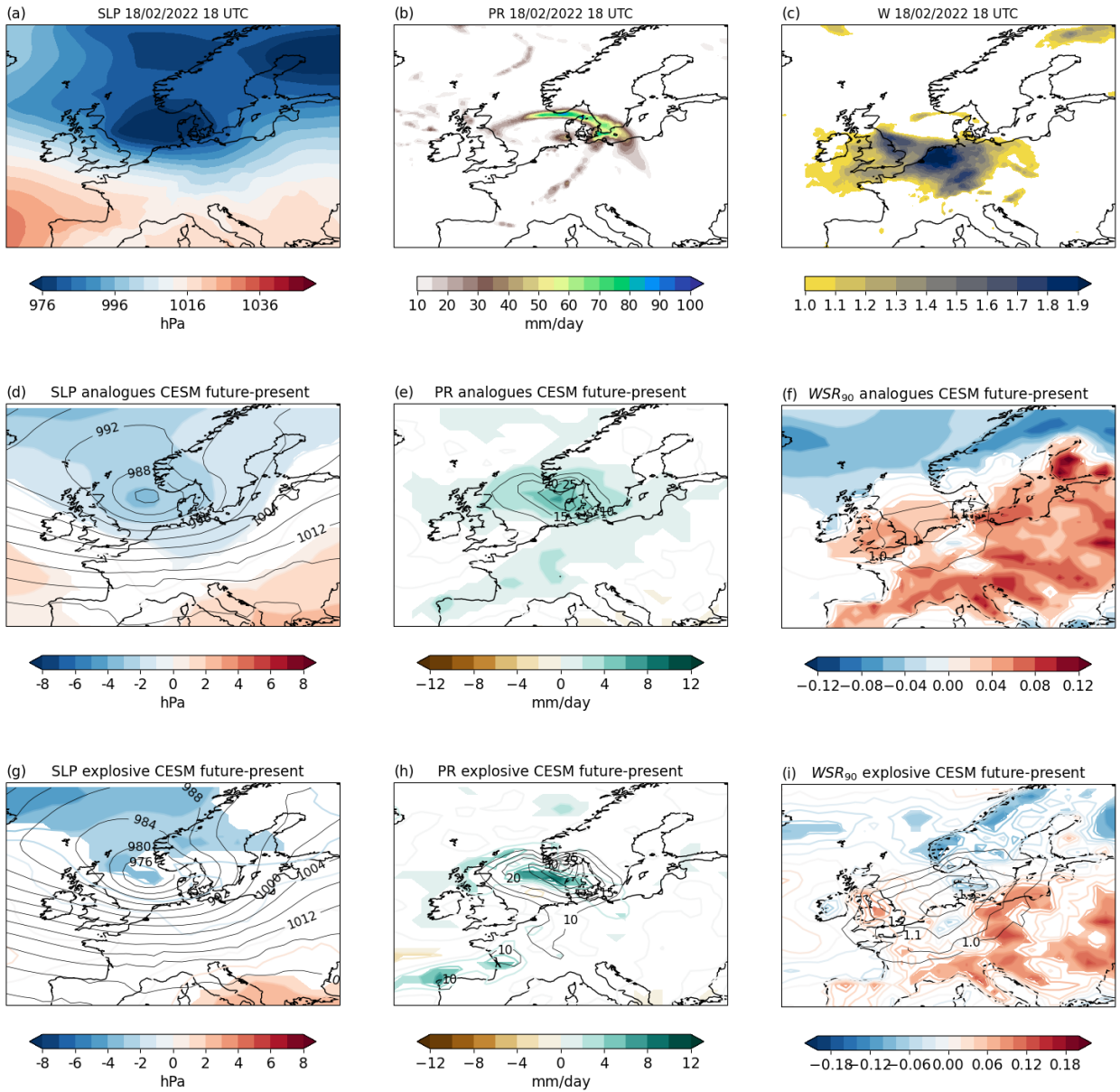


FIG. 13. Same as figure 9 but for **analogues of Eunice**.

490 Regarding the changes in $\nabla\theta_e$, figure 14c depicts an increase along a line starting in Germany
 491 and crossing central France and Bay of Biscay. This region corresponds to the southern flank
 492 of the cold front in the present climate, depicted in figure 14a in dashed white lines. Hence, the
 493 increase in $\nabla\theta_e$ can be interpreted as an intensification and a slight cyclonic shift of the cold front.
 494 This, in turn, might be linked to the increase in WSR_{90} (Fig. 13i) and increase in PR over the cold
 495 front area (Fig. 13h). On the contrary, a dipole pattern of $\nabla\theta_e$ over south Scandinavia suggests a
 496 deceleration of the warm front, shown in figure 14a as the tail of the comma-shape white dashed
 497 region.

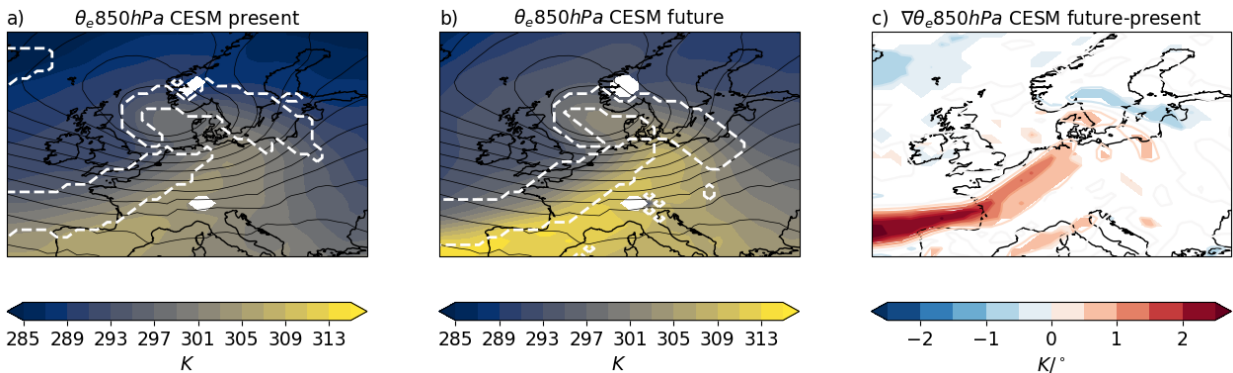


FIG. 14. Same as figure 10 but for storm **Eunice**

498 Figures 15a,b show that the jet stream is located southward and westward relative to the surface
 499 low. In the future period, the jet intensifies and extends further south. This suggests a localized
 500 increase in baroclinicity. Additionally, there is a slight increase in the northward flank exit region
 501 of the jet, which may be associated with an increase in upper-level divergence and ascent vertical
 502 motion.

503 Figure 16a shows a significant increase in the EGR 24 hours before the time 0 dates of the
 504 explosive analogues in a future period. This suggests that the changes in intensity and patterns of
 505 the explosive analogues are largely baroclinically-driven. Little changes are seen in PRECC (Fig.
 506 16b), with an increase in the cold sector of the storm. Regarding the PRECL pattern, figure 16c
 507 shows an increase over Bay of Biscay, probably linked to the increase in intensity of the cold front,
 508 as well as an increase over Denmark, where the warm front is located.

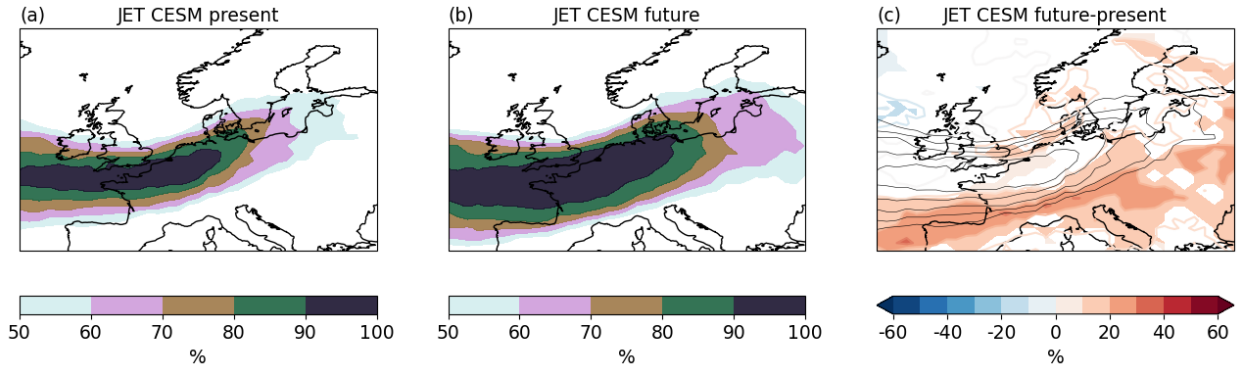


FIG. 15. Same as figure 11 but for storm **Eunice**

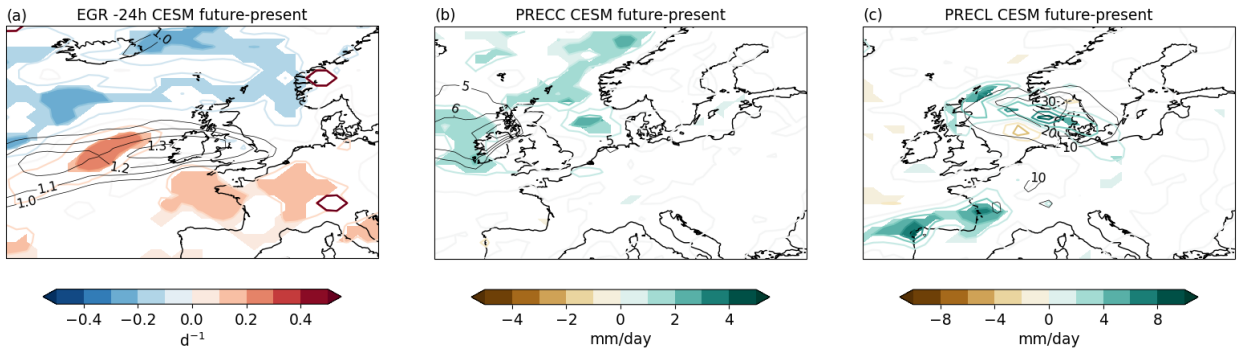


FIG. 16. Same as figure 12 but for storm **Eunice**

509 *c. Storm Xynthia*

510 The mature stage of storm Xynthia was situated over the Bay of Biscay (Fig. 17a). PR was
 511 primarily concentrated on the western flank of the storm (Fig. 17b), and the highest WSR_{90} was in
 512 the southern flank (Fig. 17c). In this context, both analogues and explosive analogues successfully
 513 capture the mature stage's position (Fig. 17d,g). Regarding the pattern of PR (Fig. 17e and Fig.
 514 17f), it is slightly shifted southwards, probably due to a misalignment between the storm fronts.
 515 Similar to storms Alex and Eunice, explosive analogues demonstrate lower SLP and higher PR and
 516 WSR_{90} than the analogues.

517 Figure 17d depicts lower pressures in the north part of the core of the analogues. In addition,
 518 there are positive anomalies of SLP in both western and eastern of the cyclonic structure, which
 519 results in an increase in the waviness of the pressure pattern. In the case of PR and WSR_{90} , both
 520 show an increase in the analogues core and northeastern of the Iberian Peninsula (Fig. 17e,f).

521 Figure 17g shows that explosive analogues depict significant lower pressures in the future period,
522 specially in their northern flank. This is linked with a significant increase in WSR_{90} (Fig. 17i).
523 Similarly to Alex (Fig. 9h), PR depicts a significant increase in the northern flank of the explosive
524 analogues' core, a slight decrease in the region of maximum PR in the present period, and a slight
525 increase in their southern flank.

526 Figures 18a,b show a different spatial pattern of θ_e at 850hPa of present and future explosive
527 analogues of Xynthia. In the present period, the warm sector of the storm does not overlap with
528 the storm center. In contrast, in the future period the θ_e at 850hPa pattern has a T-bone structure,
529 typical of the Shapiro–Keyser storms (Shapiro and Keyser 1990), and that could indicate a warm
530 seclusion sector of the storms. In terms of changes in the gradient of θ_e , there is an overall increase
531 of the gradient in the regions of the maximum gradient depicted by white dashed lines in 18a,b,
532 which are the regions associated to the weather fronts. This is related to an increase in intensity of
533 the weather fronts. A dipole with negative anomalies over the Bay of Biscay and positive anomalies
534 northwestward suggest a cyclonic shift of the warm front position, even though the overall change
535 is an increase in magnitude.

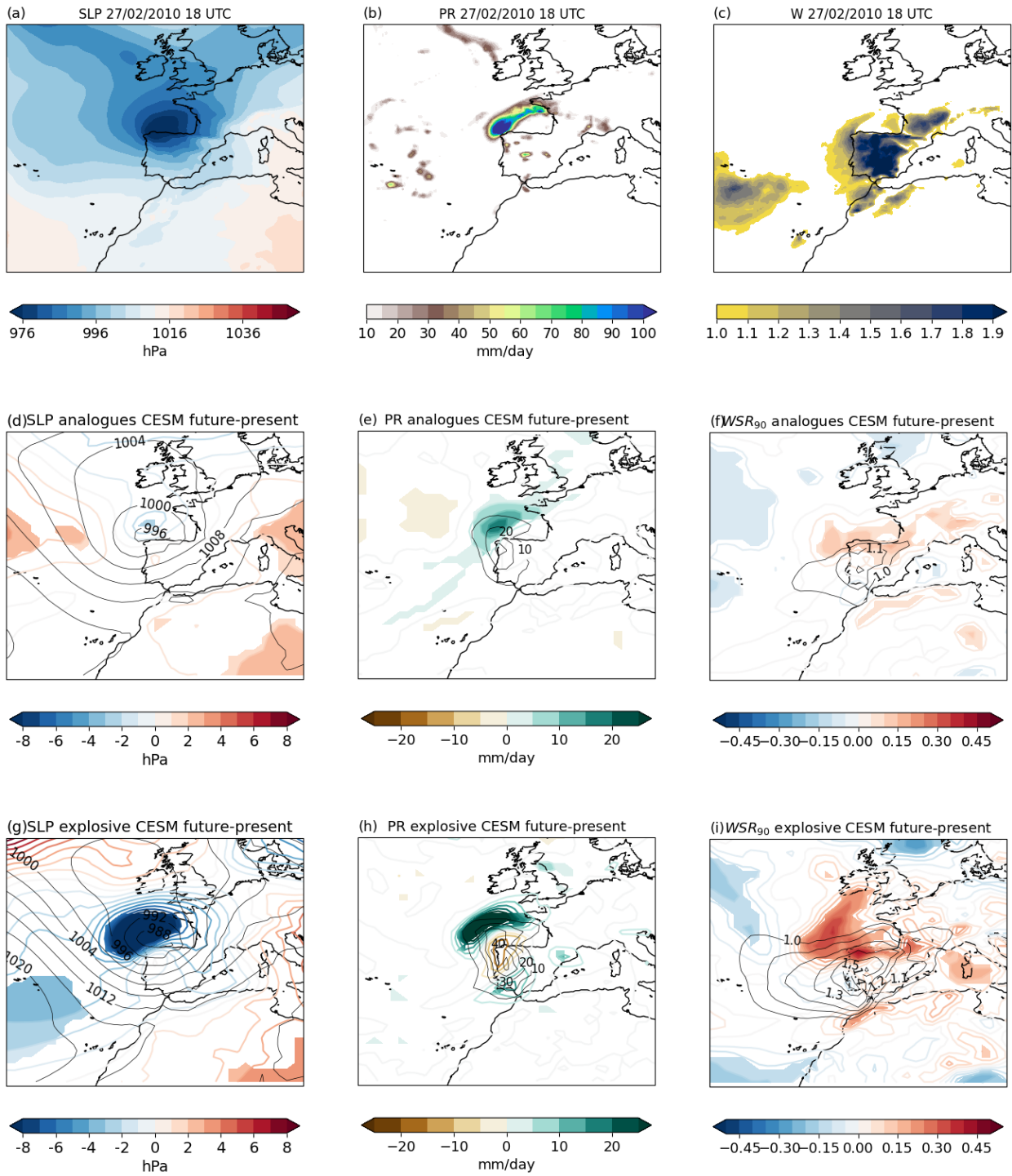


FIG. 17. Same as figure 9 but for analogues of Xynthia.

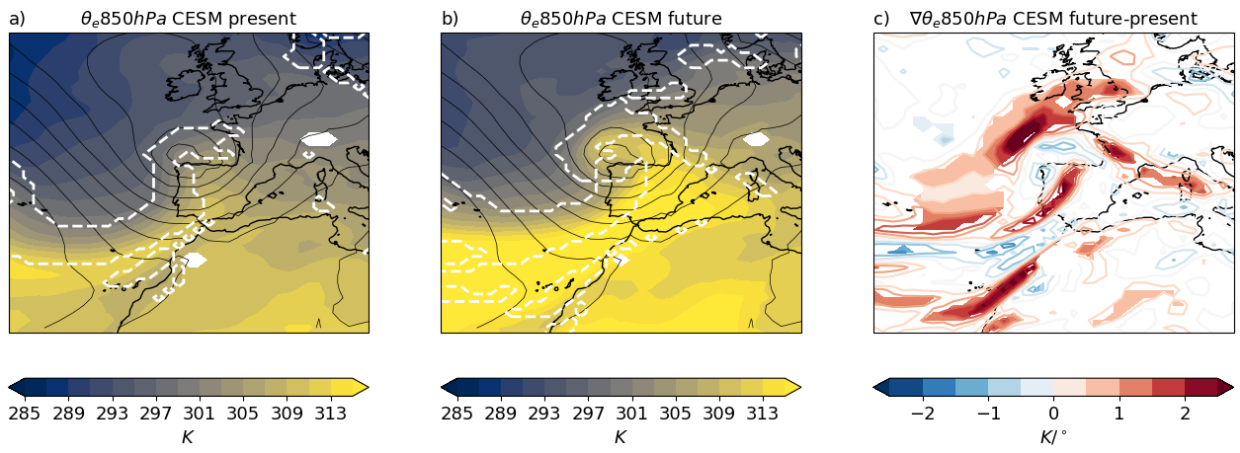


FIG. 18. Same as figure 10 but for storm **Xynthia**

536 Similar to storm Alex, Xynthia-like storms depict an extension downstream and southward of the
 537 jet stream in the future period (Fig. 19c). As previously discussed, this could lead to an increase
 538 in the vertical motion from the ageostrophic component of the wind and could be linked to the
 539 increase in precipitation and intensity of the storms. In addition, this position of the jet stream
 540 depicts a more advanced stage of the cyclone, and could be linked to the cyclonic relocation of the
 541 weather fronts.

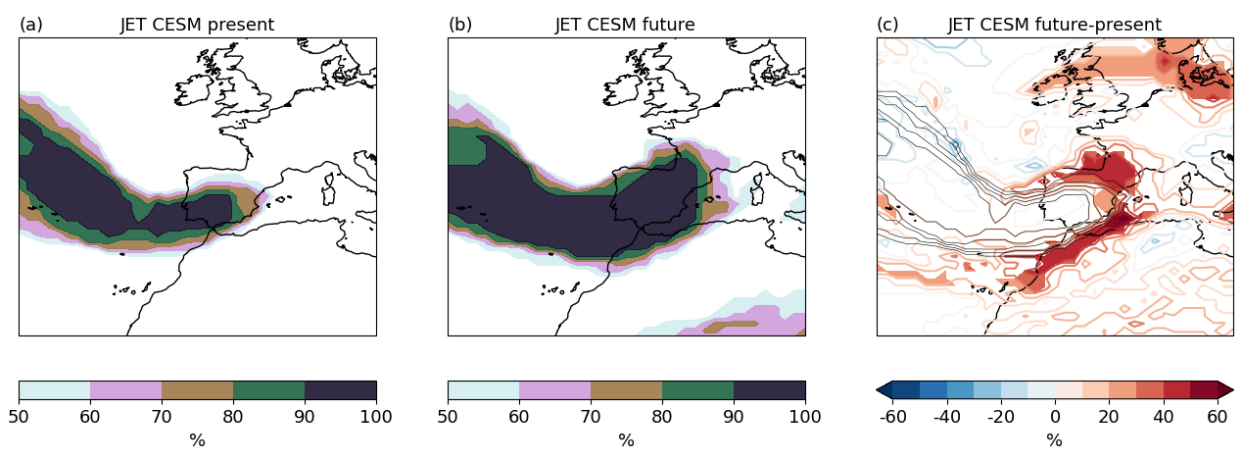


FIG. 19. Same as figure 11 but for storm **Xynthia**

542 Figure 20a depicts no change of the EGR in the region of its maximum, which means there are
 543 no changes in low-level baroclinicity 24 hours before the mature stage. Thus, changes assessed
 544 previously might be largely diabatically-driven. Regarding PRECC and PRECL (Fig. 20b,c)

545 spatial patterns, there is an overall increase in both types of precipitation. However, both show a
 546 tripolar pattern: a decrease in the core of the maximum precipitation area, and an increase in the
 547 southern and northern flanks. In the case of PRECL, this is linked to the cyclonic shift of the warm
 548 front and an intensification of both warm and cold fronts.

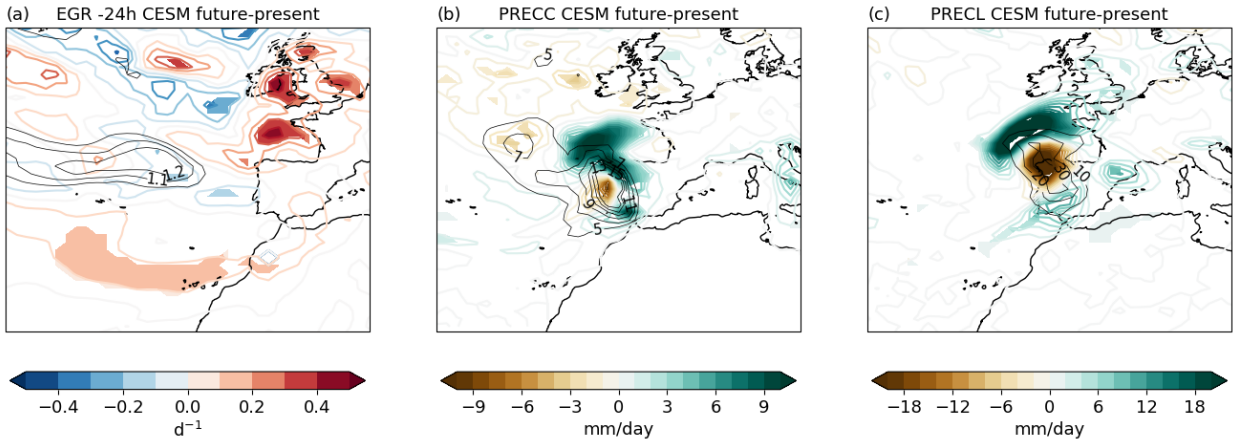


FIG. 20. Same as figure 12 but for storm **Xynthia**

549 **7. Discussion and conclusions**

550 We have conducted an analysis of three storms (Alex, Eunice, and Xynthia) under anthropogenic
 551 radiative forcing, using the CESM-Large Ensemble. We identified storms with a similar devel-
 552 opment stage to the three storms, and termed them *analogues*, in the present period (1991-2001)
 553 and in the future RCP8.5 period (2091-2100). We further selected those undergoing explosive
 554 cyclogenesis (*explosive analogues*). We found that the frequency and intensity of the analogue
 555 storms, as well as their associated meteorological hazards, will change in a future climate.

556 For storm Alex, a significant decrease in the number analogues has been observed, specially in
 557 autumn. However, there is an increase in the relative frequency of explosive analogues as well
 558 as in the normalized deepening rates. Both analogues and explosive analogues will be associated
 559 with overall higher precipitation and stronger wind speeds. The large-scale precipitation pattern
 560 of the explosive analogues and the weather front disposition suggest a cyclonic shift of the mature
 561 stage of the storms. There is a small increase in the baroclinicity in the future explosive analogues,
 562 which makes changes in their characteristics both baroclinically and diabatically driven. These
 563 factors suggest that explosive Alex-like storms will not be less frequent in a future climate. When

564 they occur, they will deepen more rapidly and be associated with higher precipitation and wind
565 speeds, indicating that storms like Alex could be a greater meteorological hazard in the future.

566 For storm Eunice, rather than a change in the number of analogues, there is a seasonal shift
567 towards more analogues in winter and fewer elsewhere. However, we found a significant increase
568 in the number of analogues that undergo explosive cyclogenesis. The quality of both analogues
569 and explosive analogues, computed using the Euclidean distance between the development stage
570 of the storm and its analogues, also increases in a future climate. This means that analogues in
571 the future climate are more similar in terms of tracks compared to the present, thereby increasing
572 the likelihood of identifying more Eunice-like storms. Additionally, there will be an increase in
573 precipitation rate and wind speed of the analogues and explosive analogues. These changes in
574 the characteristics of explosive analogues are, at least partially, baroclinically-driven. Therefore,
575 explosive Eunice-like storms will not only be more frequent but also more severe in a warmer
576 climate.

577 We found it difficult to identify good analogues of storm Xynthia in both reanalysis and climate
578 models. Hence, we can claim that storm Xynthia was an unusual event, and that a caveat of this
579 study is the quality of its analogues. We observed a decrease in the number of analogues, specially
580 in spring, but a slight increase in the relative frequency of explosive cyclogenesis. Xynthia-like
581 storms are expected to have higher precipitation rates and wind speeds in a future climate. The
582 explosive analogues depict an overall significant increase in precipitation and wind speed, with
583 a cyclonic shift in their mature stage. Changes in the patterns of explosive analogues are likely
584 to be largely diabatically-driven, as there is no change in low-level baroclinicity previous to the
585 mature stage of the storms. Therefore, Xynthia-like storms are becoming less probable but more
586 severe, especially those that are explosive, in a warmer climate. However, we acknowledge the low
587 confidence in the results that arises from the limited quality and quantity of analogues available.

588 Changes in the number of analogues, including explosive ones, depend on the specific storm
589 under consideration. Eunice-like explosive storms are expected to be more frequent, in line with
590 previous studies that project a slight increase in explosive frequency close to the British Isles and
591 on the North Sea (Seiler and Zwiers 2016; Zappa et al. 2013). The relative frequency of explosive
592 storms like Alex and Xynthia is also expected to increase with respect to the non explosive storms.
593 The increase in precipitation associated with storms in a future climate is consistent with other

594 studies (Hawcroft et al. 2018; Zhang and Colle 2017; Michaelis et al. 2017; Reale et al. 2022). For
595 the explosive analogues of Alex and Xynthia, we found a similar precipitation changes to Sinclair
596 et al. (2020). Sinclair et al. (2020) found, using aquaplanet simulations, a poleward displacement
597 of the region of maximum precipitation, mainly due to changes in the large-scale precipitation
598 pattern, in a future climate. There is less confidence in future projections regarding the dynamical
599 intensity, such as wind speed, associated to the storms (Seneviratne et al. 2021; Catto et al. 2019).
600 However, our study reveals that, across all the storms analysed, surface winds are expected to
601 increase, specially for the explosive analogues and over land. For Eunice, the increase is located
602 over the warm sector of the storms, as consistent with previous studies (Priestley and Catto 2022;
603 Dolores-Tesillos et al. 2022). The drivers behind the changes in the pattern of the storms, whether
604 they are baroclinically-driven or diabatically-driven, vary depending on the storm. However, as
605 found by Dolores-Tesillos et al. (2022), Binder et al. (2023), and Joos et al. (2023), diabatic effects
606 play a key role in increasing the wind speed, the deepening rates, and the intensity of the strongest
607 storms. For the case of Xynthia, Ludwig et al. (2014) found that the storm intensification was
608 mainly led by anomalously high sea surface temperatures and diabatic processes, and also suggested
609 that Xynthia-like storms could be more frequent in a warmer climate. We note that we found no
610 changes in low-level baroclinicity for Xynthia-like storms during the development stage. Hence, we
611 suggest that diabatic processes contribute to the increase in wind and precipitation for Xynthia-like
612 explosive storms in a future climate, as well as a relative increase of the explosive frequency,
613 consistent with the prediction by Ludwig et al. (2014). In addition, Sinclair et al. (2020) found,
614 using an aquaplanet model, that storms in a warmer climate are more diabatically-driven. To better
615 understand the potential influence of diabatic effects on storm intensification, a comprehensive
616 study on the role of warm conveyor belts in storm intensification (Binder et al. 2023) could be
617 conducted. Our study thus identifies both similarities and differences when compared to previous
618 research on various behaviors of extratropical and explosive storms in the North Atlantic under
619 climate change. These findings not only emphasize the differences in regional changes but also
620 suggest that storms may exhibit distinct behaviors compared to the overall changes, potentially
621 yielding different responses to anthropogenic radiative forcing.

622 Our approach has limitations that should be acknowledged. First, our analysis is based on a
623 single model, the CESM model version 1, which was chosen for its availability as a large ensemble

624 dataset of more than 100 members with 6-hourly data. While CESM has been shown to simulate
625 the characteristics of storms fairly well (Dolores-Tesillos et al. 2022; Joos et al. 2023; Binder et al.
626 2023) and to have a spread due to internal variability comparable to the CMIP5 multi-model spread
627 (Kay et al. 2015), it has certain biases that should be acknowledged. The model underestimates the
628 number of cyclones, specially over the ocean, as well as the deepening rates of the most extreme
629 cyclones. Moreover, our analysis is based on a small sample of cyclones, which may not fully
630 represent the entire spectrum of cyclone behavior. While the model reproduces cyclone frequencies
631 and deepening rates well within this limited sample, a multi-model study would provide a more
632 comprehensive assessment of model uncertainty. Second, we use a single scenario, the worst-case
633 scenario (RCP8.5), due to its availability. This scenario represents an extreme case assuming high
634 greenhouse gas emissions throughout the 21st century. Although this extreme scenario proves
635 valuable in detecting the anthropogenic radiative forcing signal, it may not encompass the entire
636 range of future climate projections. Therefore, our findings may not be generalized to other
637 scenarios. Future studies should explore the robustness of our results using multiple models and
638 scenarios. Finally, we use a single tracking scheme. However, we filter out the weakest storms,
639 and so the dependence on the tracking scheme is considered minor (Neu et al. 2013).

640 The analogues are considered recurrences in the atmospheric patterns of to the storms, and so
641 our results can also be applied to the explosive analogues found in the ERA5 dataset, some of them
642 being known high-impact storms in the region (Table A1). In conclusion, we found that all of
643 the storms analyzed in this study are expected to become more severe and impactful with climate
644 change. As suggested by Shepherd (2016), demonstrating that certain extreme events can occur
645 again and result in even worse consequences with climate change, as shown in this study, can help
646 advocate for investment in protective measures against hypothetical risks. Hence, these storms can
647 serve as reference points for building resilience and preparing for future events.

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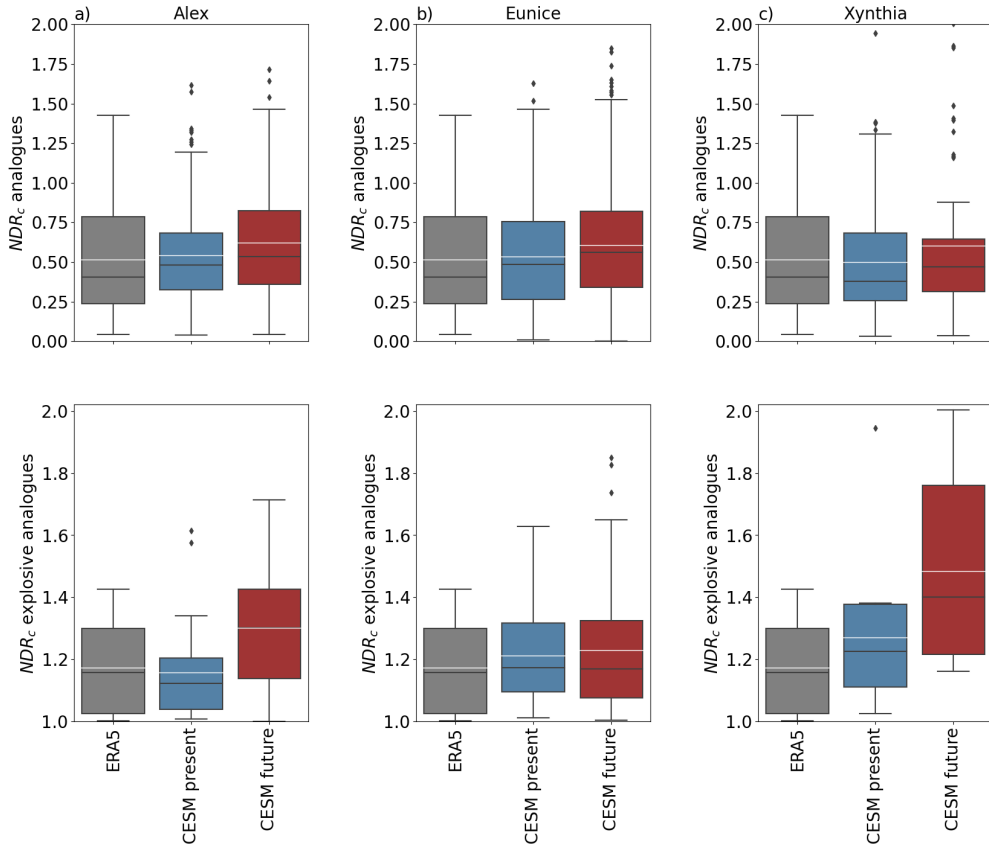
654 *Data availability statement.* The ERA5 data are publicly available online at
655 <https://cds.climate.copernicus.eu/>. We acknowledge the Atmospheric Dynamics and Climate
656 Physics groups at ETH Zurich for providing access to CESM data.

657

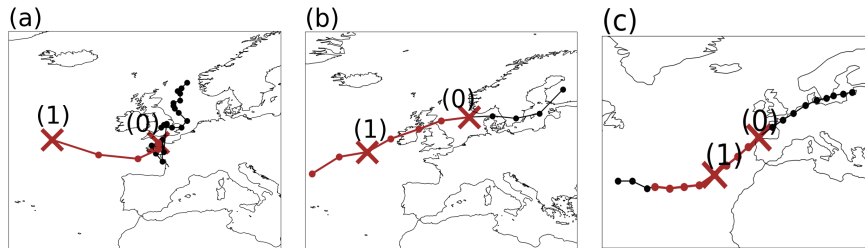
APPENDIX

Alex			
Storm Angus	20 November 2016	United Kingdom, France	Also known as storm Nanette in France. The event left 2 fatalities and wind gusts up to 170 km/h (Sky News 2016; Met Office 2016; The telegraph 2016).
Storm Norberto	5 March 2020	France, Spain	Wind gusts around 100 km/h and up to 140 km/h were recorded (The European Forecaster 2021; AEMET 2021)
Storm Katie	28 March 2016	France, United Kingdom	The highest windgust recorded was 170 km/h in Isle of Wight (The European Forecaster 2021; AEMET 2021)
Eunice			
"Adolph Bermphohl" storm	23 February 1967	North Sea	The Adolph Bermphohl was a sea rescue cruiser on which its crew died due to the severity of the storm in the North Sea. Other boats also sank in the same storm (The Wreck Site 2017).
October storm	17 October 1967	Norway, Sweden	Hurricane-force winds of up to 144 km/h were recorded in some parts of southern Sweden (SMHI and Institute 2021).
Storm Capella	3 January 1976	Ireland, United Kingdom, Belgium, France, Denmark, Germany, Netherlands	Also known as Ruisbroek flood in Belgium. The storm resulted in severe wind damage across western and central Europe and coastal flooding. One of the strongest windgusts recorded during the event was 215 km/h at Lowther Hills (Met Office 1976). It left at least 82 fatalities (Berz 1988).
Burns' Day storm	25 January 1990	Ireland, United Kingdom, France, Belgium, Netherlands, Germany, Denmark	Also known as Storm Daria. Hurricane-force wind gust were recorded, such as 167 km/h at Abertporth (McCallum 1990) and 176 km/h at Pointe du Raz (Météo France 2019). The storm left at least 95 fatalities across Europe, being one of the deathliest storms in Europe (Météo France 2019).
Storm Oratia	30 October 2000	France, Germany, Netherlands and United Kingdom	Storm Oratia (Tora in Norway) (Extreme Wind Storms Catalogue n.d.) was probably the worst storm to hit United Kingdom after the Great Storm of 1987 (NASA Earth Observatory 2017). The storm brought heavy rainfall and strong winds to many areas of southern Britain, with wind gusts up to 150 km/h.
Storm Ulli	3 January 2012	United Kingdom, Ireland, Netherlands, Scandinavia	Storm Emil in Norway (The Nordic Page Norway n.d.). The damages were estimated at 0.2 billion USD (Koks and Haer 2020; Roberts et al. 2014b)
Storm Bronagh	21 September 2018	United Kingdom	Wind gusts up to 125 km/h recorded in the Isle of Wight (Met Office 2018).
Storm Christoph	21 January 2021	United Kingdom	The event was characterized by heavy precipitation above 100 mm. This was one of the wettest 3-day periods on record in the western and northwestern part of England and Wales (Met Office 2021).
Xynthia			
Storm Miguel	6 June 2019	Spain, France, Belgium, Luxembourg, Netherlands	The storm brought high winds and heavy precipitation to western Europe, with wind gusts up to 150 km/h (AEMET 2020; EUMETSAT 2019). It caused at least three deaths.

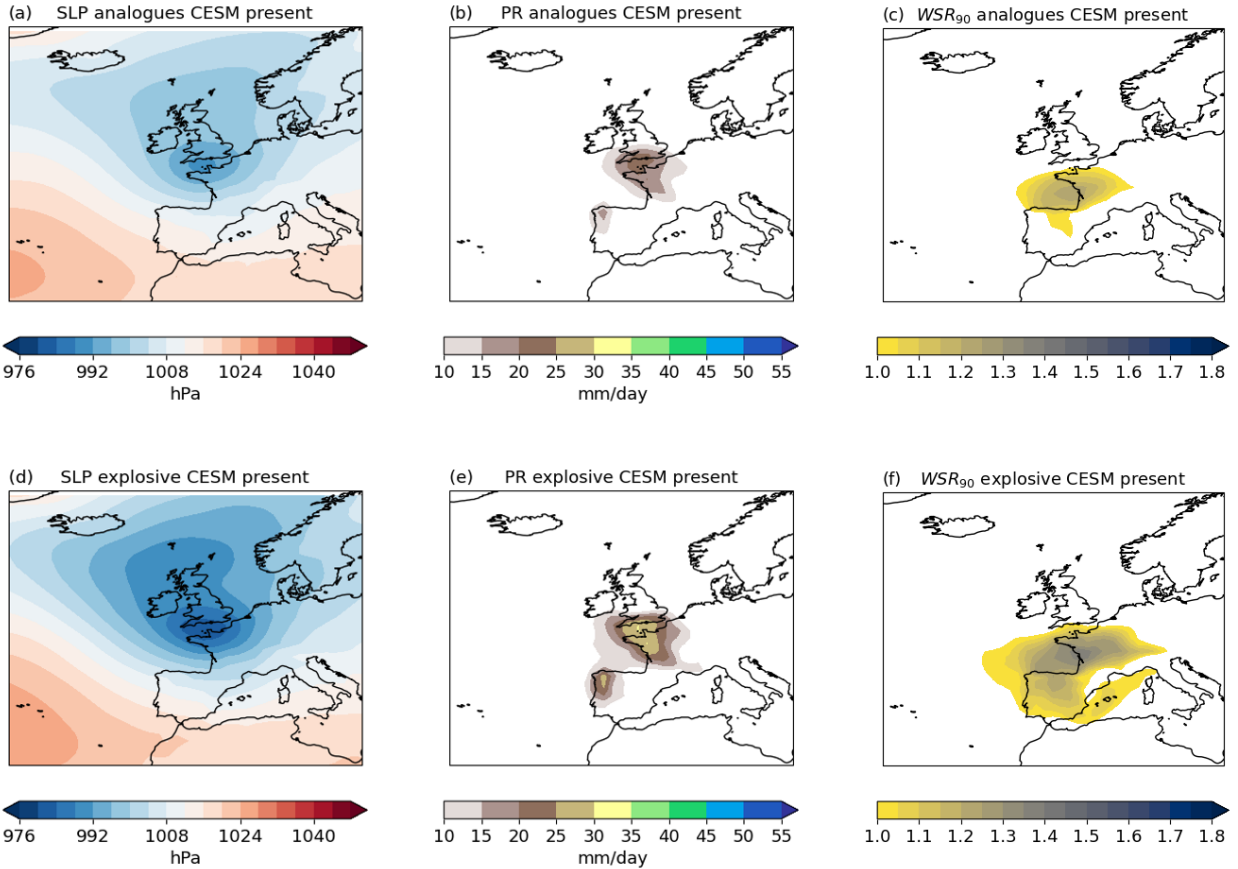
658 TABLE A1. Explosive analogues of each storm detected with ERA5, which are also known storms that had an
659 impact across Europe. The first column corresponds to the storm name, the second column shows the date of
660 minimum sea level pressure, the third column lists the regions affected, and the fourth column provides notes on
661 some meaningful aspects.



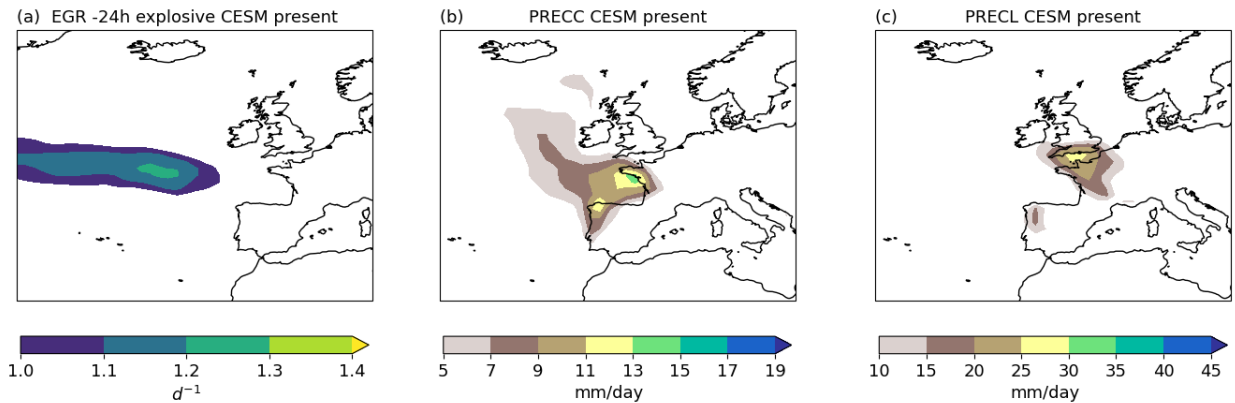
662 FIG. A1. Boxplot distributions of the Normalized Deepening Rates (NDR_c) of analogues (top row) and
 663 explosive analogues (bottom row) for Alex (a), Eunice (b), and Xynthia (c). Horizontal black lines represent the
 664 interquartile ranges of the distribution, while the white horizontal line indicates the mean values.



665 FIG. A2. 6-hourly tracks of storms Alex (a), Eunice (b), and Xynthia (c). (0) depicts the minimum sea level
 666 pressure point, and (1) the position of the storm 24 hours before (0). The brown line indicates when the storm
 667 underwent explosive cyclogenesis.



668 FIG. A3. Composites of the CESM present **analogues** and **explosive analogues** of **Alex** at their *time 0* dates
 669 of (a,d) sea-level pressure, (b,e) hourly mean precipitation rate, and (c,f) hourly mean wind speed.



670 FIG. A4. Composites of the CESM present **explosive analogues** of **Alex** at their *time 0* dates of (a) eady
 671 growth rate, (b) hourly mean convective precipitation, and (c) hourly mean large-scale precipitation rate.

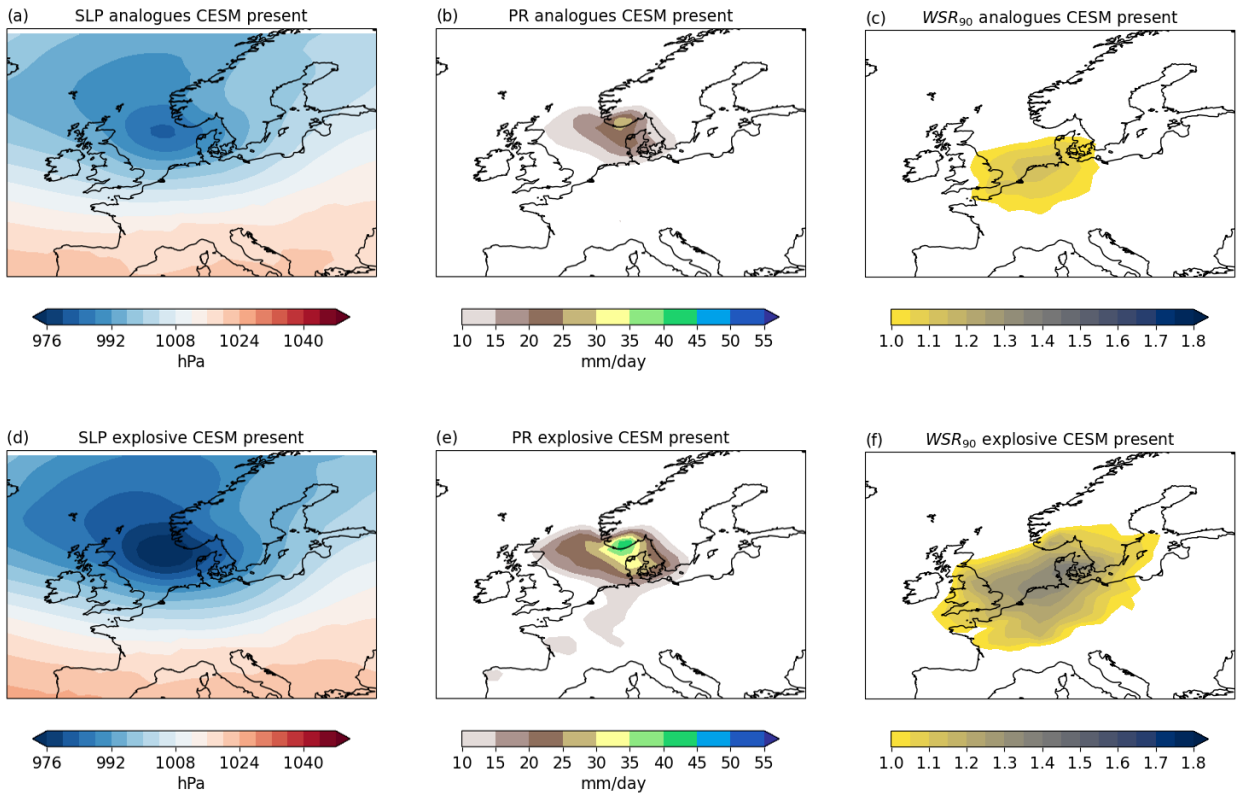


FIG. A5. Same as figure A3 but for **analogues of Eunice**.

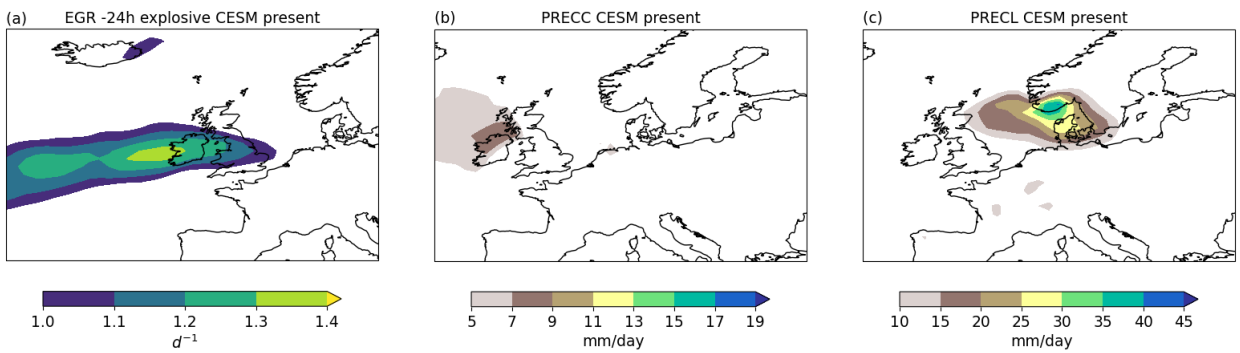


FIG. A6. Same as figure A4 but for **explosive analogues of Eunice**

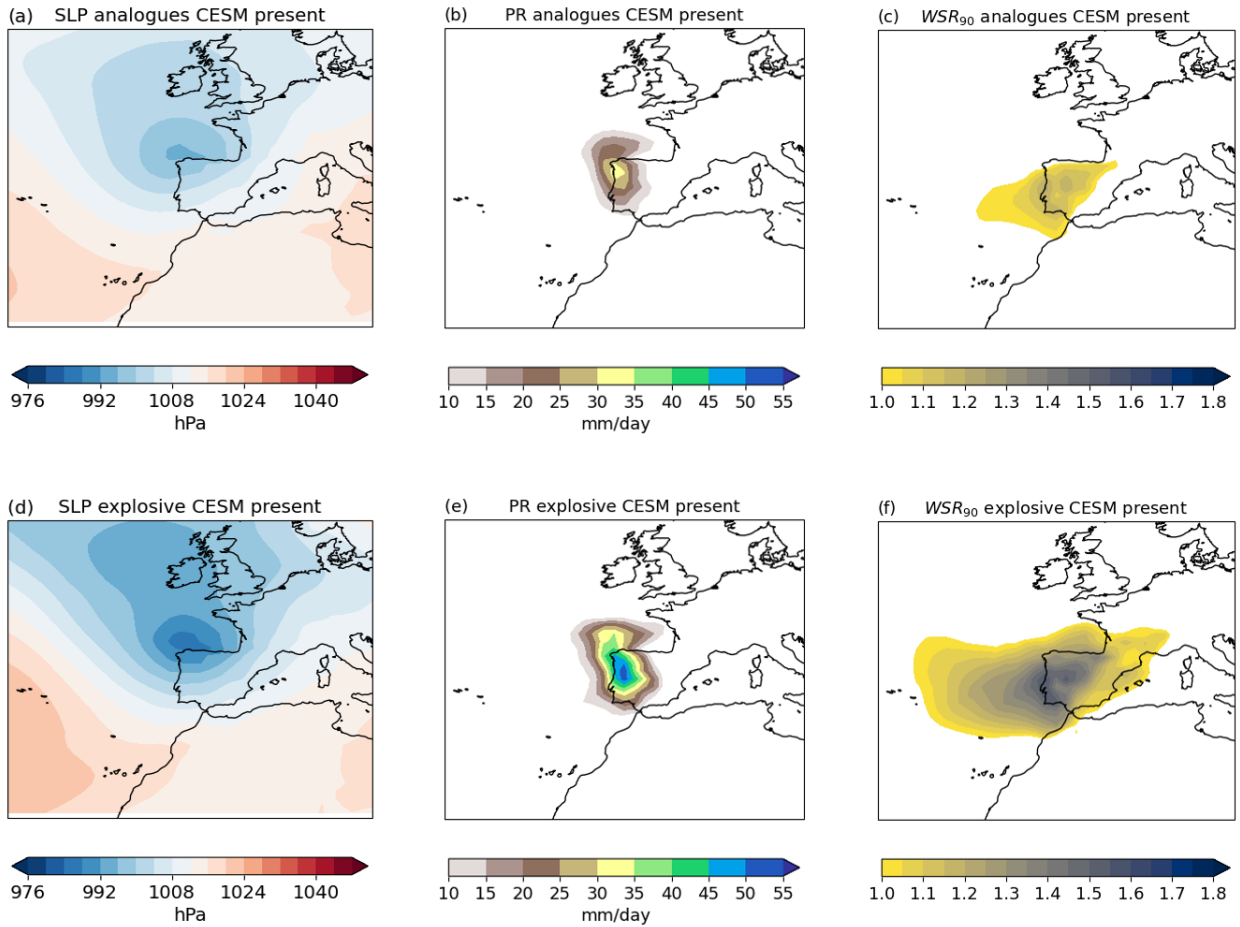


FIG. A7. Same as figure A3 but for **analogues of Xynthia**.

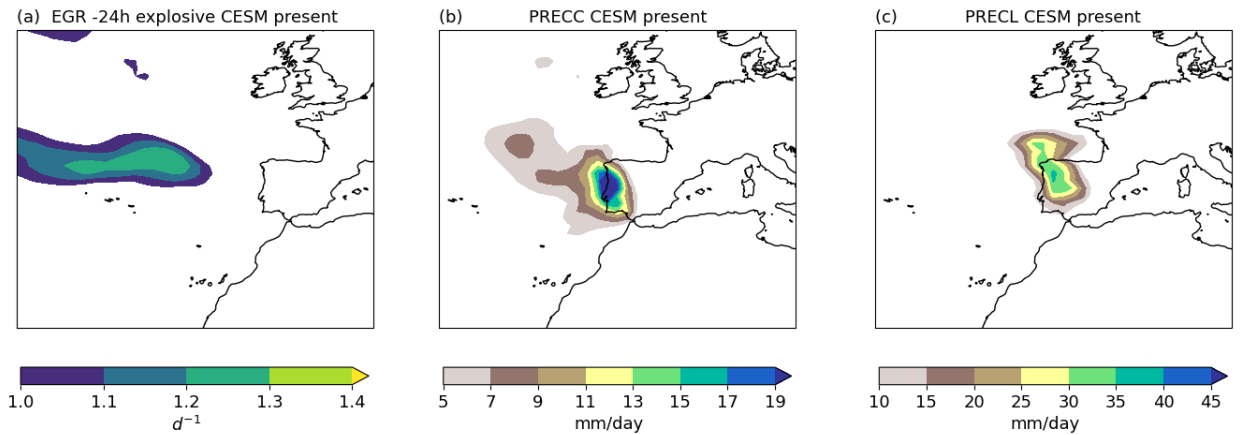


FIG. A8. Same as figure A4 but for **explosive analogues of Xynthia**

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