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1           A methodology for attributing severe  
2           extratropical cyclones to climate change  
3           based on reanalysis data: the case study of  
4           storm Alex 2020

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22                                   **Abstract**

23           Extreme event attribution aims at evaluating the impact of climate  
24           change on specific extreme events. In this work, we present an attribu-  
25           tion methodology for severe extratropical cyclones, and test it on storm  
26           Alex. Alex was an explosive extratropical cyclone that affected South-  
27           ern France and Northern Italy at the beginning of October 2020. The  
28           methodology exploits mathematical properties of circulation analogues,  
29           and identifies changes in physical and statistical properties. We first

30 divide 6-hourly ERA5 data into two periods: a counterfactual period  
31 (1950–1984) and a factual period (1986–2021). We then identify the 30  
32 cyclones in each period whose sea-level pressure maps are closest to  
33 Alex’s map by selecting those with the lowest Euclidean distance from  
34 Alex. We term these “analogues” of Alex. We find that analogues in  
35 the factual period are more persistent than in the counterfactual period,  
36 which may favour severe impacts resulting from persistent strong winds  
37 and heavy precipitation, as was the case for Alex. This effect is com-  
38 pounded by the doubling in accumulated daily precipitation detected  
39 in Northern Italy between the counterfactual and factual analogues. In  
40 the factual period, the analogues display an increase in the eddy kinetic  
41 energy in their growth phase, with poleward-shifted backward tracks. We  
42 also identify a seasonal shift of the analogues, from spring to autumn.  
43 Finally, the analogues in the factual period are closer to Alex than in the  
44 counterfactual period. These changes collectively point to high-impact  
45 storms like Alex having become more common in a changing climate.

46 **Keywords:** Extratropical explosive cyclones, Extreme Event Attribution,  
47 Climate Change, Analogues

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55 comments.

## 56 1 Introduction

57 Under global warming, the atmosphere is experiencing dynamic and ther-  
58 modynamic changes (Allan et al, 2021). Understanding and predicting such  
59 changes is an essential step in order to evaluate climate-related hazards today  
60 and in the future (Pörtner et al, 2022). A major effort in this direction has  
61 been achieved with extreme event attribution (EEA) (National Academies of  
62 Sciences, Engineering, and Medicine, 2016). EEA is an emerging field that  
63 originated in the early 2000s (e.g. Stott et al, 2004) whose objective is to esti-  
64 mate to what extent climate change influences the likelihood and severity of  
65 specific extreme climate events. Extreme event attribution combines statistical  
66 analyses and physical understanding (Stott et al, 2016), and has been applied  
67 to a broad range of extremes events, including droughts, cold spells, heatwaves  
68 or extreme rainfall events (e.g. Philip et al, 2018; Cattiaux et al, 2010; Stott  
69 et al, 2004; Jézéquel et al, 2018; Pall et al, 2011).

70 Some extreme event categories have nonetheless proved more difficult to  
71 analyse in an attribution framework than others. An example are extratropical  
72 cyclones (ETCs), whose location, frequency and intensity depend on a combi-  
73 nation of large-scale, synoptic-scale and smaller dynamic and thermodynamic  
74 features (Shapiro et al, 1999). This makes it challenging to both understand  
75 recent trends in ETC occurrence and project future ones (e.g. Shaw et al, 2016).  
76 In the Northern Hemisphere (NH), the number of ETCs has likely increased  
77 in recent decades (Chang and Yau, 2016), while there is evidence of a decrease  
78 in the number of NH extreme cyclones in winter (Neu et al (2013), referred  
79 to as deep cyclones) and in summer (Chang et al (2016), referred to as strong  
80 cyclones). However, there is low confidence for such changes as they are sub-  
81 ject to high internal variability and regional variations and they are sensitive  
82 to the choice of reanalysis (Tilina et al, 2013) and cyclone detection and  
83 tracking methods (Neu et al, 2013). In future climate projections, the num-  
84 ber of ETCs in the storm track regions is projected to decrease globally, while  
85 the number of extreme cyclones is likely to increase in NH winter (Priestley  
86 and Catto, 2022). As stated in the last IPCC report, the precipitation asso-  
87 ciated with ETCs over the NH (Seneviratne et al, 2021) and the number of  
88 ETCs associated with extreme precipitation (Lee et al, 2021) are projected to  
89 increase (high confidence). However, there is a less clear response regarding  
90 wind speed changes, which are expected to be small and subject to regional  
91 variations (Seneviratne et al, 2021).

92 These global or hemispheric-scale changes mask a number of important  
93 regional trends, although in many cases it may be difficult to determine to  
94 which extent these depend on long-term climatic changes or on low-frequency  
95 internal climate variability. For example, in the North Atlantic, there is evi-  
96 dence of an overall poleward shift of the storm track between 1979 and 2010  
97 (Tilina et al, 2013). The same authors state that very deep cyclones (<960  
98 hPa) increased in frequency in the North Atlantic region from 1979 to 1990 in  
99 most reanalyses, and declined thereafter. However, such changes may be mod-  
100 ulated by the interdecadal variability of the North Atlantic Oscillation (Feser  
101 et al, 2015). Simulations of future climates from the Coupled Model Inter-  
102 comparison Project phases 5 and 6 (CMIP5 and CMIP6) project a tripolar  
103 anomaly pattern in winter North Atlantic storm track, with an extension of  
104 storm activity further into Europe and a decrease on the storm track's north-  
105 ern and southern flanks (Harvey et al, 2020; Zappa et al, 2013; Priestley and  
106 Catto, 2022). CMIP5 models and Regional Climate System Models from the  
107 Med-CORDEX initiative also show a weakening of the storm activity over  
108 the Mediterranean region (Zappa et al, 2015; Reale et al, 2022). However,  
109 according to the last IPCC report (Lee et al, 2021), there is low confidence  
110 in regional change projections in the NH and especially in the North Atlantic  
111 in winter due to "large natural internal variability, the competing effects of  
112 projected upper- and lower-tropospheric temperature gradient changes, and  
113 new evidence of weaknesses in simulating past variations in North Atlantic  
114 atmospheric circulation on seasonal-to-decadal timescales".

115 The uncertainty surrounding past and future regional trends in ETCs high-  
116 lights the difficulty in attributing their occurrence to climate change. Here, we  
117 present an attribution methodology applicable to severe extratropical cyclones,  
118 and test it on storm Alex: an explosive cyclone that affected France and Italy  
119 in October 2020. We demonstrate that a combination of analogue analysis,  
120 dynamical systems theory and extreme value theory enables to attribute the  
121 characteristics and impacts of individual extratropical cyclones to the ongoing  
122 climatic changes.

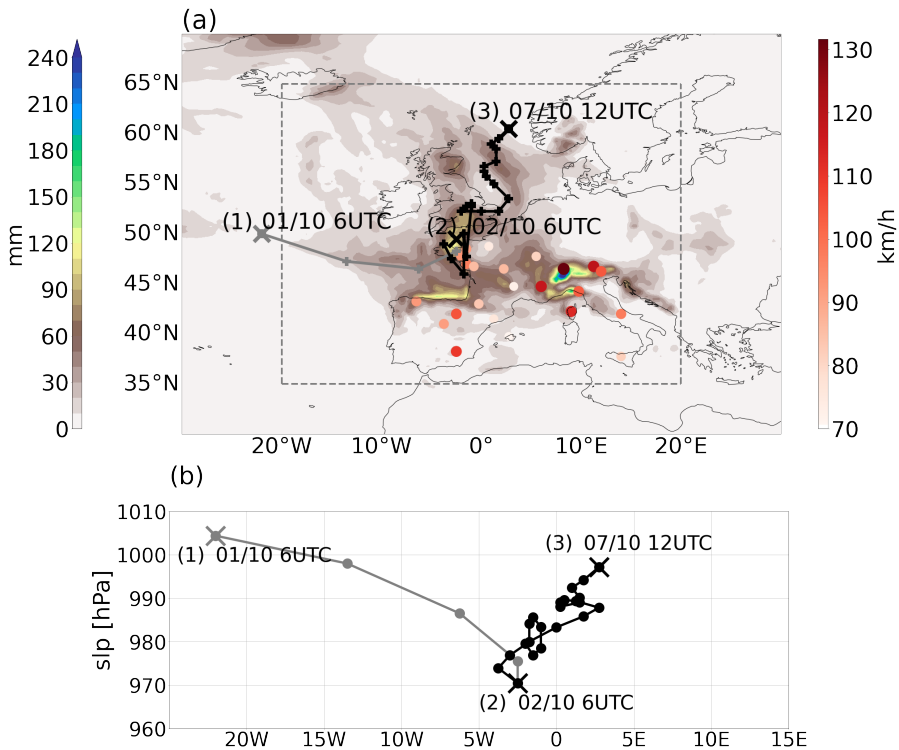
123 The paper is organized as follows: section 2 describes the characteristics of  
124 Alex. Section 3 provides a detailed description of the data and methods used.  
125 It is followed by the presentation of the results in section 4 and a discussion  
126 and conclusion in section 5.

## 127 **2 Alex: a high-impact explosive cyclone**

128 Storm Alex was a powerful explosive cyclone (Sanders and Gyakum, 1980; Neu  
129 et al, 2013) that affected south-western Europe in October 2020. It formed as  
130 a small perturbation south of Greenland and was named by Météo-France on  
131 the 1st of October. Favoured by a very strong jet stream with core speeds of  
132 up to 100 m/s, Alex deepened rapidly and experienced explosive cyclogenesis  
133 between the 1st and the 2nd of October with a deepening rate of 1.62 Bergeron.  
134 The cyclone made landfall in Brittany on the night between the 1st–2nd Octo-  
135 ber, with very intense surface winds of up to 140 km/h that caused widespread  
136 damage. On the 2nd of October in the early morning the cyclone reached its  
137 minimum pressure with values around 970 hPa (such as 969,6hPa in Vannes,  
138 France (Météo France, 2021)). The size of the cyclone was about  $2 \times 10^6$  km<sup>2</sup>,  
139 with an effective radius of 810 km, computed using the area enclosed in the  
140 last closed isobar with 1 hPa step using the ERA5 reanalysis dataset (Hers-  
141 bach et al, 2020). Alex then remained stationary over the English channel for a  
142 day. Southeasterly winds were induced in southern France and northern Italy,  
143 carrying warm, humid air from the Mediterranean and producing extremely  
144 heavy rainfall and strong winds. This phenomenon is known as a Mediter-  
145 ranean episode (WMO, 2020). On the 3rd of October the cyclone weakened  
146 and moved to Normandy. Finally, on the 4th of October, Alex headed north-  
147 ward to England and dissipated during the following days over the North Sea.  
148 Figure 1 shows Alex’s backward and forward trajectories. It also shows the  
149 maximum wind gusts over land and the total accumulated precipitation over  
150 the domain between the 1st and the 4th of October at 06:00 UTC. As a caveat,  
151 it is possible that not all the precipitation and wind gusts displayed in Figure  
152 1 are directly associated with storm Alex.

153 The persistence of storm Alex over the same region resulted in severe  
154 impacts, especially in southern France and northern Italy. The area located  
155 windward of the Alps received heavy and prolonged orographically-driven rain-  
156 fall, leading to numerous record-breaking precipitation amounts registered in  
157 the Alpes-Maritimes, Var and Piedmont regions. Piedmont had the highest

158 rainfall since 1951, recording 630 mm in 24h in Sambughetto ([European State](#)  
 159 [of the Climate, 2020](#)). Saint-Martin-Vésubie, a village in Alpes-Maritimes,  
 160 recorded 501 mm of precipitation in 24 hours ([Météo France, 2020a](#)), which  
 161 corresponds to more than three times the climatological October precipita-  
 162 tion ([Météo France, 2020b](#)). Alex caused at least 23 fatalities (10 in France,  
 163 10 in Italy, 1 in Austria, 1 in Poland and 1 in the Czech Republic), more than  
 164 10 missing people and an estimated economic loss of about 2.7 billion euros  
 165 ([Météo France, 2021](#); [Riviera 24, 2021](#); [The Watchers, 2020](#); [Aon, 2020](#)).



**Fig. 1** (a) Backward (grey) and forward (black) trajectories of storm Alex relative to its point of maximum intensity. Total accumulated precipitation (shading) and maximum 10m wind gusts (coloured dots) between 01/10/2020 at 06:00 UTC and 04/10/2020 at 06:00 UTC, when Alex had its largest impacts. The numbers indicate when cyclogenesis occurred (1), when Alex reached its minimum sea-level pressure (2), and when it underwent cyclolysis (3). Dashed lines indicate the spatial domain used to find the analogues, covering (20W–20E, 35–65N). We use ERA5 6-hourly data to track the cyclone, and ERA5 hourly data to obtain the accumulated precipitation and maximum 10m wind gusts (see Section 3 for further details). The maximum 10m wind gusts were obtained for every region of France, Italy, and Spain, using spatial masks according to NUTS2 regions ([Eurostat, 2021](#)); here we only present some regions to have a general view of the storm's impacts. (b) The corresponding sea-level pressure evolution at the cyclone center as a function of time and longitude.

## 3 Methodology

We compute flow analogues (Yiou, 2014) to find pattern recurrences of Alex in mean sea-level pressure (SLP), and assess changes in the analogues within the ERA5 reanalysis dataset (Hersbach et al, 2020). We use 6-hourly data from 1950 to 2021, which we split into two 35-year periods: a factual period, from November 1986 to November 2021, and a counterfactual period, from January 1950 to December 1984. We refer to them as [1986-2021] and [1950-1984], respectively. The latter is meant to represent a climate only weakly affected by anthropogenic emissions, while the former presumably displays a stronger anthropogenic influence. This assumption is supported by a substantial change in the effective-radiative forcing from the 1980s onwards, as shown in Figure 2.10 of Chapter 2 in the last IPCC Sixth Assessment Report, (Gulev et al, 2021), and by a significant increase in the number of storms in the North Atlantic in the factual period with respect to the counterfactual (Fig. B1). The number of storms has been counted using the *TempestExtremes* software package (Ullrich et al, 2021; Ullrich and Zarzycki, 2017; Zarzycki and Ullrich, 2017). We pick 35-year periods as a balance between needing periods that are short enough to assume a relatively constant climate state, yet long enough to assume that interannual variability issued from periodic variations such as the El-Niño – Southern Oscillation averages out. Adopting two periods around 30-year long is a common practice in attribution studies (e.g. Luu et al, 2018; Vautard et al, 2019). We have tested that changing the periods slightly (e.g. [1950-1975] and [1995-2020]) do not alter qualitatively the results.

### 3.1 Analogue circulation patterns

We identify the 2nd of October 2020 at 6:00UTC as approximately when storm Alex reached its lowest central pressure (970.48hPa according to ERA5 data) while stalling over the English Channel. We term this time step *lag 0* date of Alex. We then use mean sea-level pressure to identify the best 30 analogue cyclones in the counterfactual and factual periods. To select the analogues, we compute the Euclidean distance between the sea-level pressure maps of the 2nd of October 2020 at 06:00UTC and all other time steps at each grid point of the spatial domain covering [20W–20E, 35–65N] (dashed-line box in Figure 1a). Then, we average the Euclidean distances for all grid boxes across the domain for each timestep, resulting in a time series of domain-averages Euclidean distances. The 30 analogues are the timesteps that display the 30 smallest Euclidean distances. To avoid counting several times the same cyclone, we impose a minimum 7-day separation between analogues. This is justified by the fact that 3 days is a typical timescale for the formation and decay of an extratropical cyclone (Moon et al, 2021), but that specific cyclones can last longer than this (e.g. Alex lasted 7 days). Since our main purpose is to find distinct storms similar to Alex in order to assess changes in their dynamical characteristics, we deem a 7-day separation appropriate. Changes in the spatial domain of up to 10 degrees do not alter the results in a significant manner.

209 Some quantitative changes are however expected when the domain is modified,  
210 as the analogues include information about all atmospheric structures within  
211 the chosen domain. The choice of 30 analogues is a balance between the needs  
212 to have a large enough sample size to make statistical inferences, and to have  
213 analogues that are suitably close to the reference event we are studying. Using  
214 25 or 40 analogues rather than 30 does not change our results substantially.  
215 We have computed the average Euclidean distance of the closest 30 events  
216 for each sea-level pressure map of the two periods and found no significant  
217 differences in the probability distributions (Fig. B2). Hence, we conclude that  
218 30 analogues is a robust choice.

219 Once we have obtained the *lag 0* dates of the 30 best analogues – namely  
220 the dates when the minimum Euclidean distance for each analogue is attained  
221 – we compute their composite maps for several variables of interest for each  
222 period, and the difference map between them. Figures B3 and B4 show the  
223 mean sea-level pressure patterns at the *lag 0* dates of the 30 analogues in the  
224 counterfactual and factual period, respectively. Additional variables of interest  
225 include geopotential height at 500 hPa (Z500), eddy kinetic energy at 500 hPa  
226 (EKE500), 24-hour accumulated precipitation (PR), 2m air temperature aver-  
227 aged over 24 hours (T2M), maximum 10m wind gust within 24 hours (WG),  
228 and deseasonalized 2m air temperature (T2Mdes). EKE500 is computed using  
229 a 24-hours difference filter (Wallace et al, 1988). WG is the maximum 3-second  
230 wind at 10 m height as defined by the World Meteorological Organization  
231 (WMO, 1987), where the gust is computed at every time step and the maxi-  
232 mum is kept since the previous post-processing. To compute PR and WG, we  
233 use hourly data, and to evaluate T2M we use 6-hourly data. The start times  
234 to compute the accumulated values for PR, average values for T2M and maxi-  
235 mum values for WG are the *lag 0* dates and end times are 24 hours after  
236 them, that is, at *lag +24* hours. To evaluate T2Mdes, we first compute a 31-  
237 day running-mean smoothed seasonal cycle for each period. We then subtract  
238 the smoothed seasonal cycle from the T2M data.

239 For each analogue, we compute 48 hours backward and forward cyclone tra-  
240 jectories with a 6-hours time step using a semi-objective Lagrangian approach.  
241 Cyclone centers are automatically identified by following the absolute mini-  
242 mum sea-level pressure. We have then checked and corrected each trajectory  
243 manually if needed, which induces some subjectiveness in our method. Some  
244 cyclones originate from secondary cyclogenesis, that is, from the trailing fronts  
245 of a ‘primary cyclone’ (Parker, 1998; Priestley et al, 2020). They are typically  
246 diagnosed by a trough in the sea-level pressure configuration of the primary  
247 cyclone. Here we detect them using a semi-objective method where troughs  
248 are detected visually but are required to have a minimum depth of 5hPa. We  
249 have compared factual cyclone tracks with those obtained following Pinto et al  
250 (2005), which corresponds to the method M02 from Neu et al (2013) of the  
251 Intercomparison of Mid Latitude Storm Diagnostics (IMILAST), without find-  
252 ing any qualitative differences. Hence, the tracking method used here is not  
253 expected to alter our results and conclusions.



254 We count the number of cyclones that experienced explosive cyclogenesis  
 255 following the definition of Sanders and Gyakum (1980) as those with a Normal-  
 256 ized Central Pressure Deepening Rate (NDR, Reale et al (2019)) greater than  
 257 1. We also count the number of cyclones entering the Mediterranean region as  
 258 those that, after 24 hours or more, are located at latitudes south of 43°N and  
 259 longitudes east of 3°E.

260 We finally assess the quality of analogues. We first compute *SLP anomalies*  
 261 by subtracting Alex’s SLP from the mean SLP of the analogues in the two  
 262 periods. Second, we represent the probability distributions of the values of  
 263 the SLP Euclidean distances between Alex and its analogues and we term it  
 264 *analogues quality*.

## 265 3.2 Dynamical systems metrics

266 In order to characterise the dynamics of storm Alex and its analogues, we use  
 267 local dimension and persistence metrics issued from dynamical systems theory.  
 268 These metrics describe the local properties of a dynamical system (Lucarini  
 269 et al, 2016), which for atmospheric data may be related to the characteristics of  
 270 instantaneous regional atmospheric patterns (e.g. Messori et al, 2017; Faranda  
 271 et al, 2017; Alvarez-Castro et al, 2018; Messori et al, 2021).

272 We follow the approach from Faranda et al (2017) and Lucarini et al (2016),  
 273 who combine extreme value theory with dynamical systems theory to com-  
 274 pute the local dimension  $d$  and persistence  $\theta^{-1}$  of dynamical systems. Local  
 275 dimension  $d$  describes the phase-space geometry of the trajectories in the neigh-  
 276 bourhood of a certain state of the system. The higher  $d$ , the higher the number  
 277 of possible evolutions to and from that state. The persistence  $\theta^{-1}$  measures  
 278 the average residence time around a given state, and is given by the inverse  
 279 of the extremal index  $\theta$ .  $\theta$  has units of frequency (here 1/6 hours<sup>-1</sup>, as we use  
 280 6-hourly data). Hence, to find the persistence in hours, we multiply  $\theta^{-1}$  by a  
 281 factor of 6. A detailed description of the procedure to compute  $d$  and  $\theta^{-1}$  is  
 282 provided in Appendix A.

## 283 3.3 Assessing statistical significance

284 To assess the statistical significance of the differences between the analogues’  
 285 averages in the factual and counterfactual periods, we apply a bootstrap pro-  
 286 cedure with 1000 iterations (Wilks, 2005). Our null hypothesis is that both  
 287 sets of analogues are drawn from distributions with the same mean. If the dif-  
 288 ference of the two original samples — factual minus counterfactual — has an  
 289 absolute value larger than the 95th percentile of the bootstrap distribution, we  
 290 reject the null hypothesis and conclude that the differences are statistically sig-  
 291 nificant. To compute Confidence Intervals (CI) for statistical samples we again  
 292 apply a bootstrap procedure with 1000 iterations, with a 95% confidence level,  
 293 namely taking the 2.5th and 97.5th percentiles of the bootstrap distribution  
 294 as the lower and upper bounds, respectively. To evaluate the CI of the local  
 295 dimension  $d$  we resample the exceedances of the threshold  $s(q)$  (see section A)

296 and compute  $d$  in each iteration. To calculate the CI of the extremal index  $\theta$  we  
297 resample the inter-cluster and cluster sizes with equal probabilities (Süveges,  
298 2007), and compute  $\theta$  for each sampling iteration. Finally, the statistical sig-  
299 nificance of the differences between boxplots is assessed using a two-sample  
300 Kolmogorov-Smirnov test (Wilks, 2005), with a 5% significance level. The null  
301 hypothesis is that both data samples belong to the same, unknown distribution.

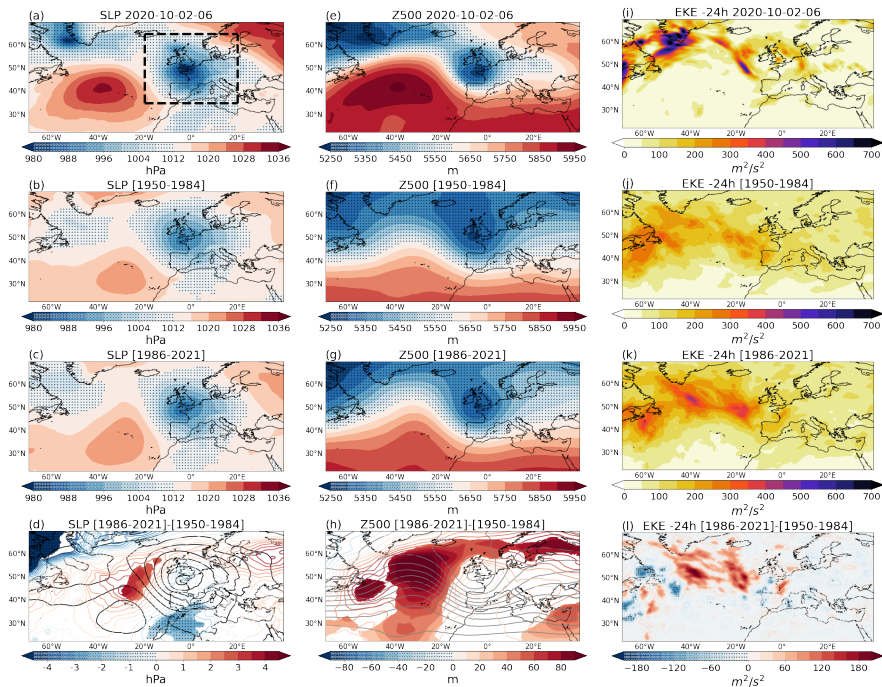
## 302 4 Results

### 303 4.1 Circulation patterns

304 Figure 2a–c shows the SLP map for the *lag 0* time step of Alex and the  
305 composite SLPs for analogues during the counterfactual and factual periods,  
306 respectively. Both sets of analogues capture the large-scale structure of Alex,  
307 albeit with a weaker magnitude as may be expected by the average of 30  
308 events. Note that when computing the Euclidean distances to find the analo-  
309 gues we use the domain shown by the dashed-line box in Fig. 1, and so the  
310 North Atlantic large-scale atmospheric configuration might differ between analo-  
311 gues. The difference between the two analogue composites (Fig. 2d) displays  
312 an SLP dipole: high pressure anomalies over the North Atlantic and low pres-  
313 sure anomalies over North Africa. This northward (southward) extension of  
314 the high (low) pressure system yields an increase in the waviness of the pat-  
315 tern in the factual period. No significant differences are found at the cyclone  
316 center. In the middle troposphere (Z500), the analogues capture the low pres-  
317 sure structure over England that characterised Alex (Fig. 2e, f, g). The Z500  
318 differences between the analogues in the two periods (Fig. 2h) partly resem-  
319 ble those in SLP: there is a northward extension and a strengthening of the  
320 Azores anticyclone, enhancing the waviness of the pressure field.

321 Fig. 3 shows Alex’s SLP and Z500 and the composite SLP and Z500 of  
322 the analogues 12 hours after *lag 0* dates, that is, at *lag +12* hours. We find  
323 negative, albeit marginally significant, SLP anomalies over the cyclone core  
324 region. In the mid-troposphere, Z500 shows high-pressure anomalies over the  
325 North Atlantic. The pattern of the background flow is thus wavier in the factual  
326 period, as for *lag 0*, due to low-pressure anomalies in the cyclone region and  
327 upstream high-pressure anomalies.

328 We further analyse the EKE500 maps for Alex and its analogues (Figure  
329 2i–l) 24 hours before *lag 0* dates, that is, at *lag -24h* hours. There is a clear  
330 difference between Alex’s EKE500 and that of the analogues in both periods,  
331 which emphasizes that the analogue storms have different origins across the  
332 North Atlantic basin. Composite EKE500 analogue differences between the  
333 two periods (Fig. 2l) show a dipole of positive anomalies west of England and  
334 weaker negative anomalies at lower latitudes, representing a poleward shift in  
335 the factual period with respect to the counterfactual. In addition, EKE500  
336 differences centered at 48 hours before Alex show this dipole but shifted about  
337 10° to the west (Fig. B5). This pattern suggests a higher-latitude origin of the  
338 storms in the factual period, consistent with the increase in the waviness found

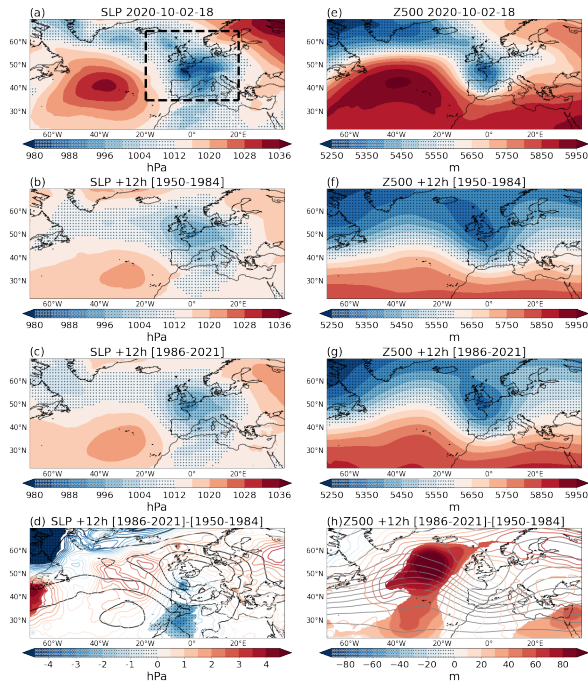


**Fig. 2** Mean sea-level pressure (a) and geopotential height at 500hPa (e) at the *lag 0* date of storm Alex and 500 hPa eddy kinetic energy (i) 24 hours prior to the *lag 0*. SLP composites of the 30 analogue storms for the counterfactual (b) and factual (c) periods, and the corresponding Z500 (f,g) and EKE500 (j,k) composites. Factual minus counterfactual differences of SLP (d), Z500 (h) and EKE500 (l). Coloured contours in (d) and (h) show the differences while grey contours show the counterfactual absolute values. Shading in (d, h, l) shows statistically significant differences. In all panels, negative and low values are stippled

339 in the SLP and Z500 maps (Fig. 2d,h). Figure 2l also shows an increase of the  
 340 maximum EKE500 over most of the North Atlantic, which implies that storms  
 341 in the factual period are more energetic in their growth phase than those in  
 342 the earlier period.

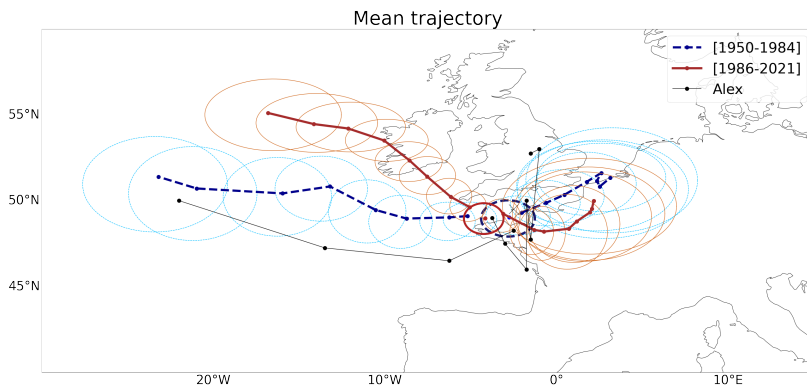
## 343 4.2 Cyclone tracking

344 To better assess changes in storm location, the tracks of the analogue cyclones  
 345 are shown in Fig. 4. There is a clear latitudinal shift in the backward trajec-  
 346 tories, that is, the trajectories of the cyclones up to 48 hours before the *lag 0*  
 347 *0* dates: in the factual period (solid red), the storms head towards Europe  
 348 from higher latitudes than those in the counterfactual period (dashed blue).  
 349 There is no overlap in the confidence intervals, which means that this shift  
 350 is statistically significant. The forward trajectory response, that is, up to 48  
 351 hours after the *lag 0* dates, is less clear, as most storms dissipate not far  
 352 upstream of the English Channel. The backward trajectory of Alex shows that



**Fig. 3** Same Fig. 2a–h, but at lag +12 dates.

353 the cyclone formed and grew at latitudes below  $50^{\circ}\text{N}$  (Fig. 4), indicating a  
 354 higher resemblance with those in the counterfactual period.

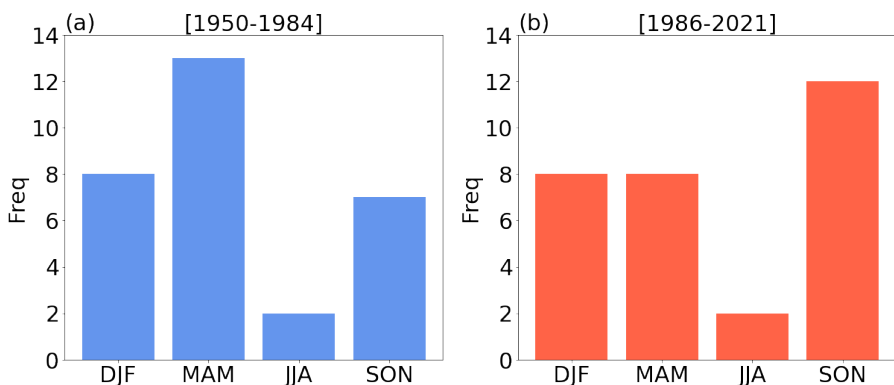


**Fig. 4** Alex’s track (black line) and average cyclone tracks for the factual (red solid line) and counterfactual (blue dashed line) periods. Dots represent cyclone locations on 6-hourly timesteps. Ellipses show the confidence interval, built using bootstrapping, for each timestep of factual (red thin solid lines) and counterfactual (blue thin dashed lines); the x-axis shows confidence intervals of longitudes and the y-axis of latitudes. Thick ellipses and dots show the confidence intervals and the average cyclone positions for the dates of the analogues, respectively.

355 A counting of explosive cyclones using the definition of Sanders and  
 356 Gyakum (1980) has been performed for both periods. In the counterfac-  
 357 tual period two analogue cyclones underwent explosive cyclogenesis, from  
 358 11/03/1976 at 6 AM to 12/03/1976 at 6 PM and from 03/10/1984 at 12 AM  
 359 to 04/10/1984 at 12 PM. The latter corresponds to storm Hortense, which  
 360 mainly affected Southwestern France (Météo France, 2019a). In the factual  
 361 period, apart from Alex itself only one explosive cyclone has been found, from  
 362 04/11/2000 at 12 AM to 05/11/2000 at 18 PM. This is cyclone Rebekka,  
 363 which had its greatest impact in Southern France (Météo France, 2019b). The  
 364 NDRs of the two explosive cyclones in the counterfactual period (1.51 and 1.50,  
 365 respectively) are larger than that of the single explosive cyclone in the factual  
 366 period (1.20). Alex has the largest NDR of our cyclone sample (1.61). The  
 367 results presented here only include a very small fraction of the North Atlantic  
 368 cyclones, and the explosive cyclone analogues found take place over a short  
 369 period of time, between the 1974 and 2000, which is not enough to attribute  
 370 the decline (from 2 explosive cyclones to 1) to any specific factor. A counting  
 371 of cyclones that ended in the Mediterranean region has also been done, and  
 372 we find 3 in the counterfactual world and 5 in the factual. This increase in  
 373 frequency may be linked to the increase in waviness seen previously, although  
 374 the results found here are insufficient to draw conclusions on the tendency of  
 375 the number of Atlantic cyclones reaching the Mediterranean.

### 376 4.3 Seasonality of analogues

377 Figure 5a,b shows that in the counterfactual period Alex-like storms were more  
 378 common in spring while in factual conditions they occur chiefly in autumn.  
 379 The number of analogues in winter and summer remains unchanged over the  
 380 two periods.

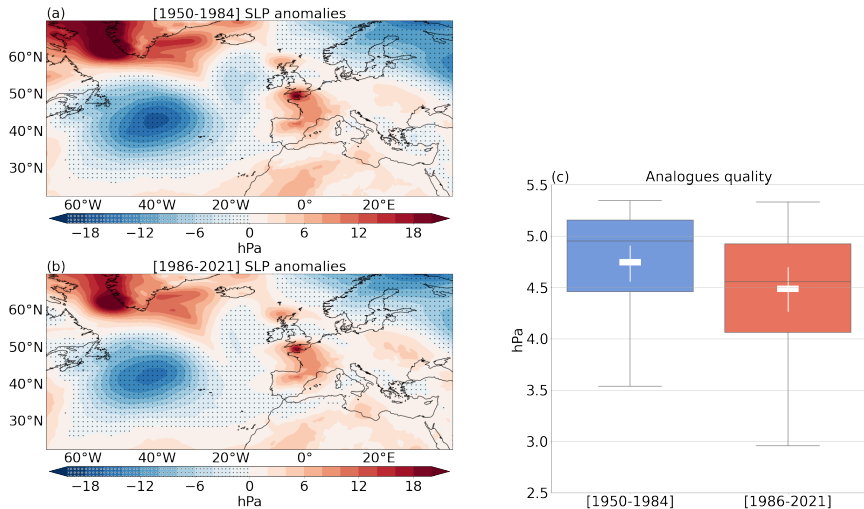


**Fig. 5** Frequency of analogues per season, namely winter (DJF), spring (MAM), summer (JJA) and autumn (SON), for the counterfactual (a) and factual (b) periods.

381 The dynamical changes observed in figure 2d,h,l and 4, i.e., a wavier pres-  
382 sure pattern, a strengthening of the eddy activity, and a poleward shift of the  
383 backward trajectories, may be linked to either a direct or an indirect climate  
384 change signal. In the former, climate change would act to shift poleward and  
385 strengthen Alex's analogues directly. In the latter, climate change leads to a  
386 seasonal shift in the occurrence of analogue storms, and the observed changes  
387 correspond to the changes in the mean behavior of the cyclones according  
388 to the season of most frequent occurrence. The two effects are not exclusive,  
389 and changes may reflect a combination of direct and indirect signals. To help  
390 evaluate these two hypotheses, we search for 30 analogue storms in autumn  
391 (September-October-November) and 30 in spring (March-April-May) for each  
392 period and repeat the analysis of Sect. 4.1 and 4.2. Z500 field shows a wavier  
393 pattern, that is, a northward extension of the high pressure systems, in the fac-  
394 tual period during autumn (Fig. B6), while in spring the pattern is less clear  
395 (Fig. B7). SLP maps show a deepening of the cyclone over France in autumn,  
396 and again a less clear pattern in spring. Hence, we attribute the wavier pat-  
397 tern and the increase in cyclone depth to: (i) a seasonal shift of the analogues  
398 from spring to autumn; and (ii) changes in autumn pressure patterns, when  
399 Alex occurred. This response could be then a combination of: (i) an indirect  
400 and (ii) a direct climate change signal, even though the proportion of (i) and  
401 (ii) is difficult to quantify. The mean tracking shows a clear poleward shift  
402 of backward and forward trajectories in spring, while in autumn the shift is  
403 weaker (Fig. B8).

#### 404 4.4 Quality of Analogues

405 Figure 6a,b shows that composite SLP anomalies over the North Atlantic are  
406 smaller in the factual than in the counterfactual period. Figure 6c shows the  
407 distributions of the analogues quality. The set of factual cyclones provides  
408 better analogues than the cyclones from the counterfactual period. We also  
409 compute pressure anomalies and analogues quality for spring and autumn ana-  
410 logues separately (Fig. B9 and B10, respectively). Spring anomalies are larger  
411 over the North Atlantic compared to autumn ones in both periods. In the coun-  
412 terfactual period, analogues quality is better in spring than in autumn, which  
413 highlights the similarity of Alex with spring storms. In other words, Alex is  
414 more similar to analogue cyclones in spring in the counterfactual period, while  
415 the North Atlantic atmospheric circulation pattern associated with Alex is  
416 closer to that of the autumn analogues, consistent with the pressure field sea-  
417 sonality (Alex occurred in October). However, the quality of autumn analogues  
418 improves significantly in the factual world, while in spring there is almost no  
419 difference between the counterfactual and factual periods. We thus conclude  
420 that Alex was a "black swan" in autumn in the counterfactual period, and  
421 rather reflected the characteristics of spring cyclones. However, in the factual  
422 period the number of autumn analogues is rising (Fig. 5) and the quality is  
423 improving.



**Fig. 6** Sea-level pressure anomalies of counterfactual (a) and factual (b) periods, and box-plots of analogues quality (c). The white horizontal lines show the means of each distribution and the white vertical lines the corresponding confidence intervals.

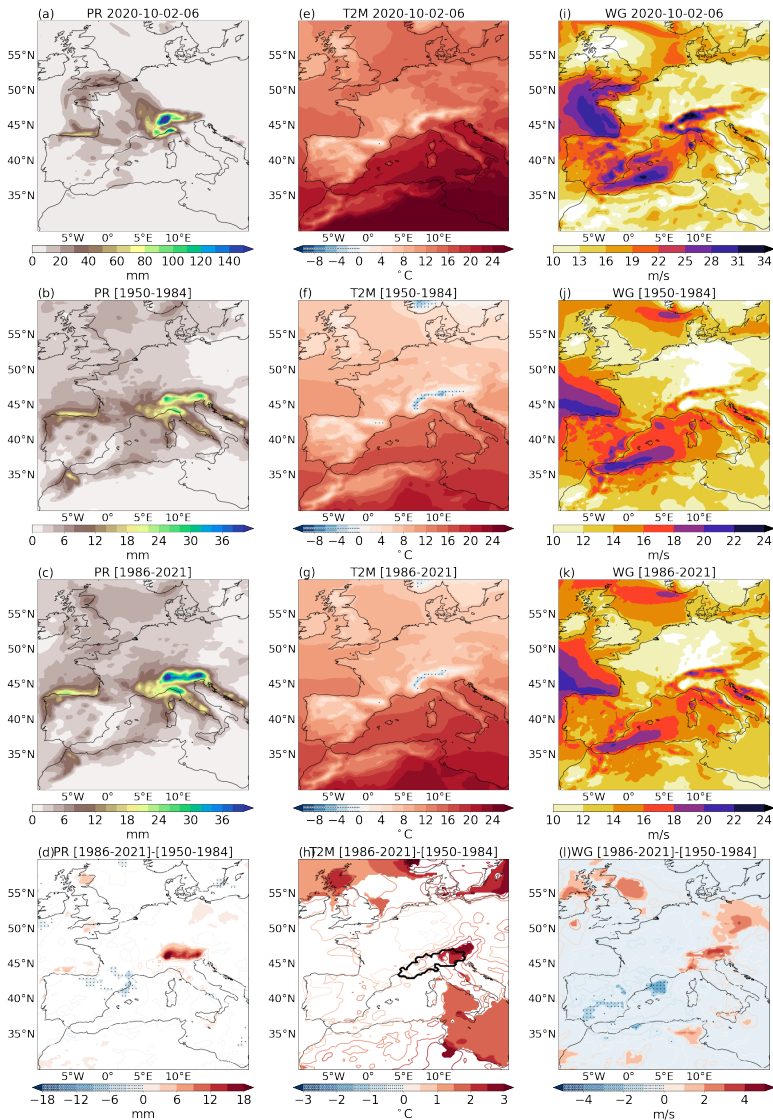
## 424 4.5 Impacts

425 In this section, we evaluate three surface fields to detect differences between  
 426 factual and counterfactual impacts: PR, T2M and WG.

427 Alex generated heavy precipitation in southern and eastern France and  
 428 northern Italy (Fig. 7a). The analogues averages (Fig. 7b,c) also show a signifi-  
 429 cant amount of precipitation over this region in both periods, although much  
 430 lower than storm Alex. There is also much weaker precipitation in southern  
 431 England, central France and Northern Spain compared to Alex. This may be  
 432 ascribed to a combination of weaker analogue cyclones and some variability in  
 433 their position that leads to aliasing in the composite. Figure 7d shows a signifi-  
 434 cant increase in precipitation between the counterfactual and factual analogues  
 435 of more than 12 mm in 24 hours windward of the Alps, a region that suffered  
 436 catastrophic consequences from Alex.

437 The increase in rainfall, probably linked to the Stau effect, is accompanied  
 438 by a rise in 2m air temperature (Fig. 7h) leeward of the Alps, linked to the  
 439 Foehn effect. In addition, there is a significant increase in temperature by  
 440 more than 1.5 K over the eastern Mediterranean, the northeastern Atlantic  
 441 Ocean, and the Baltic Sea. This increase can be due to a direct climate change  
 442 signal, or it can reflect a shift in the seasonality of the analogues. To better  
 443 assess these changes, we repeated the analysis on the deseasonalized T2M field  
 444 (Fig. B11). We did not find significant changes between the counterfactual and  
 445 factual periods, meaning that the T2M signal over the Alps and sea regions is  
 446 mainly due to a shift in seasonality.

447 Figure 7l shows an increase of the 10m maximum wind gust in the Alps,  
 448 Liguria and Provence of up to 5 m/s. Increasing accumulated precipitation

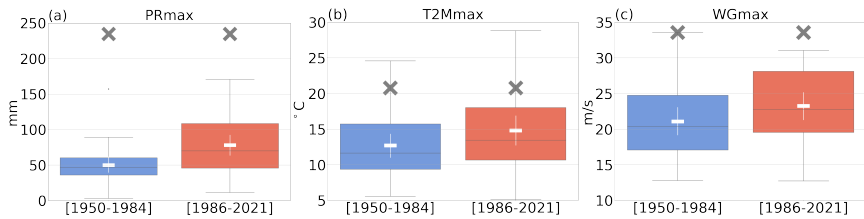


**Fig. 7** 24-hour accumulated precipitation for Alex (PR, a), counterfactual analogues (b), factual analogues (c), and difference between the two periods (d). Daily average of 6-hourly 2-meter air temperature for Alex (T2M, e), counterfactual analogues (f), factual analogues (g), and difference between the two periods (h). Maximum 10m wind gust within 24 hours for Alex (WG,i), counterfactual analogues (j), factual analogues (k), and difference between the two periods (l). Note that color bars in (a),(i) and (b,c),(j,k) are different. The thick black contour in (h) shows the spatial mask applied in the analysis of Fig. 8 and covers the *target region* formed by: Provence-Alpes-Côte d’Azur, Liguria, Piemonte, Lombardia, Valle d’Aoste, Provincia Autonoma di Bolzano, Veneto, Provincia Autonoma di Trento and Friuli-Venezia Giulia.



449 and maximum wind gust imply that factual cyclones are a greater hazard.  
450 24-hour mean 10m meridional wind (Fig. B12) shows positive anomalies over  
451 the Ligurian Sea and the Gulf of Venice, which enhances the advection of  
452 warm, humid air from the Mediterranean to Northern Italy and Southeastern  
453 France (Fig. B12h). This increase in meridional wind, related to an increase in  
454 the meridional SLP gradient, can also yield the increase in precipitation seen  
455 previously (Fig. 7d, h).

456 To further quantify the observed increase in precipitation and temperature  
457 in northern Italy and southern France, we first apply a spatial mask (Fig. 7h)  
458 to limit the analysis to the regions of highest impacts for Alex and greater  
459 differences between the counterfactual and factual analogues. This delimited  
460 region is referred to as *target region* in the remaining text. For Alex's *lag 0*  
461 time step, we compute the 99th quantile of PR, T2M and WG over the *target*  
462 *region*. We then compute the (spatial) average values above this quantile in  
463 the *target region*. This procedure is also applied to the analogues. We term the  
464 (spatial) averages maximum precipitation (PRmax), maximum temperature  
465 (T2Mmax) and maximum wind gust (WGmax). Hence, we can determine the  
466 different probability distributions of PRmax, T2Mmax and WGmax, linked to  
467 an Alex-like storm, in the two periods (counterfactual and factual; Fig. 8). We  
468 find that PRmax during Alex is much higher than the rest of the analogues,  
469 reaching almost 250 mm. The means of PRmax for the analogues are around  
470 50 mm in the counterfactual period and 80 mm in the factual period. In addition,  
471 in the factual period the 75% quantile of the boxplot exceeds 100 mm of  
472 rain, while it barely reaches 60 mm in the counterfactual. Hence, in the factual  
473 period there is an increase in maximum rainfall. T2Mmax during Alex is  
474 higher than that of most of its analogues. There is also a shift of the T2Mmax  
475 distribution towards higher maximum temperatures in factual conditions by  
476 about 2°C. WGmax during Alex is higher than that of the analogues in factual  
477 world but comparable with the counterfactual maximum. WGmax mean  
478 and median values increase from counterfactual to factual periods by about 2  
479 m/s. PRmax distribution differences between the two periods are statistically  
480 significant, while the T2Mmax and WGmax differences are not. We repeated  
481 the analysis of Fig. 8 but for the full domain to find the analogues (dashed-line  
482 box in Fig. 1), and applying a land-sea mask for the wind gusts. We have found  
483 qualitatively different results for the wind gusts but similar for precipitation  
484 (not shown). In the case of wind gusts, the differences in the probability distributions  
485 are likely due to features of the synoptic circulation away from the  
486 *target region*. We found that 8 analogues in the counterfactual period and 12 in  
487 the factual have their highest wind gusts over the *target region*. Regarding the  
488 precipitation, the region of maximum precipitation of most of the analogues,  
489 that is, 22 in the counterfactual period and 25 in the factual, corresponds to  
490 the region of highest precipitation of Alex.



**Fig. 8** Boxplot of the area-averaged values above the 99% quantile over the *target region* for PR (a), T2M (b) and WG (c). The white horizontal lines show the means of each distribution and the white vertical lines the corresponding confidence intervals. Grey crosses show the values of Alex.

## 4.6 Dynamical system metrics

Table 1 shows a decrease in  $d$  in the factual world with respect to the counterfactual, which means that the most recent climate has fewer possible evolutions than the counterfactual one. In addition,  $\theta^{-1}$  shows that factual period storms are  $\sim 4$  hours more persistent than the counterfactual period ones (Table 1). Hence, the sea-level pressure pattern is more persistent in the factual period, increasing the stationarity of the cyclonic systems. The differences in  $d$  and  $\theta^{-1}$  are both statistically significant. The decrease in  $d$  and the increase in  $\theta^{-1}$  point to an increase in the intrinsic predictability, as low values of  $d$  and high of  $\theta^{-1}$  are associated with high-predictability configurations (Messori et al, 2017; Faranda et al, 2017; Hochman et al, 2019). While this result is obtained specifically for severe cyclones, it is in line with the results found in Faranda et al (2019) and Scher and Messori (2019) who, using two independent approaches, argued for an increasing predictability of the midlatitude atmosphere.

	[1950-1984]	[1986-2021]	Change %
$d$	7.5 [6.6 8.3]	6.8 [6.1 7.6]	-8.5
$\theta^{-1}$	20.8 [18.9 22.7]	24.1 [21.4 26.8]	15.7

**Table 1** Local dimension  $d$  (unitless) and persistence  $\theta^{-1}$  (hours) in the counterfactual (first column) and factual (second column) periods, and the relative changes in the factual with respect to the counterfactual period (third column). Values in brackets show confidence intervals.

## 5 Discussion and Conclusion

We have presented a methodology for the attribution of severe extratropical cyclones and their impacts to ongoing climate change. We specifically applied this to storm Alex, which struck southern and western Europe in October 2020. We based our analysis on 30 analogue storms (Yiou, 2014) for Alex in factual (with strong climate change) and counterfactual (with limited climate change) periods from ERA5, and their dynamical properties.

512 A comparison of the two sets of analogues evidences that the factual storms  
513 typically occur on the background of a wavier atmospheric pattern than the  
514 counterfactual storms. This stronger meridional component of the flow is likely  
515 linked to a slower-moving wave pattern (Screen and Simmonds, 2014), as  
516 also highlighted by a persistence index we computed using dynamical system  
517 theory. This shows an average 4h increase in the persistence of atmospheric  
518 patterns in the factual world. Previous studies also found an increase in persist-  
519 ent circulation regimes in recent years (Alvarez-Castro et al, 2018; Hoffmann,  
520 2018), and some suggest a possible link with Arctic Amplification (Cohen et al,  
521 2018; Yao et al, 2017; Kornhuber and Tamarin-Brodsky, 2021). The observed  
522 amplified low-level warming at high latitudes in the NH (Serreze et al, 2009)  
523 would act to weaken the zonal wind via the thermal wind relationship, result-  
524 ing in an increase in amplitude of the polar jet meandering and slower wave  
525 propagation, and favouring the longer persistence of weather patterns that lead  
526 to extreme events. However, due to the complexity of the eddy-mean flow feed-  
527 backs, the underlying dynamics are not entirely clear (Hoskins and Woollings,  
528 2015). In addition, a challenge arises in distinguishing the forced signal from  
529 the internal variability (Mann et al, 2017; Barnes and Screen, 2015), partly due  
530 to an incomplete knowledge of the influence of high-latitudes on mid-latitude  
531 weather as well as a lack of data (Cohen et al, 2014). Hence, according to the  
532 last IPCC report, "there is low to medium confidence in the exact role and  
533 quantitative effect of historical Arctic warming and sea-ice loss on mid-latitude  
534 atmospheric variability" (Doblas-Reyes et al, 2021). Further analysis linking  
535 sea-ice loss with the present work's findings could be performed, although the  
536 lack of reliable sea ice data before 1978 complicates the study.

537 We further find that, in the factual period, cyclones like Alex are more  
538 energetic in their growth phase, as seen by an increase in the eddy kinetic  
539 energy at *lag -24* hours. They also display lower pressures at *lag +12* hours  
540 during the decay phase of the storms. This interpretation assumes that *lag 0*  
541 corresponds also to the mature stage for the analogues of Alex. The analogues  
542 also tend to occur more frequently in autumn and less frequently in spring.  
543 However, this does not imply an a priori influence on storm intensity, as the  
544 two seasons are comparable in this respect (Hoskins and Hodges, 2019). When  
545 separating analogues according to season, autumn analogues have been found  
546 to undergo a large increase in cyclone intensity, which may be related to an  
547 increase in humidity leading to an increase in moist baroclinic instability and  
548 maximum EKE500 of baroclinic eddies (Gutowski Jr et al, 1992). Sinclair and  
549 Watterson (1999) also suggests that an enhancement in water vapor content  
550 and a localized increase in baroclinicity could increase regional storm activity.  
551 In addition, an increase of the land-sea contrast due to a faster warming over  
552 land than over the ocean (Jia et al, 2019) could enhance baroclinicity in sum-  
553 mer and early autumn, yielding to an increase of the cyclones intensity. Further  
554 investigation using ad hoc numerical model simulations would be required to  
555 analyse this and discern the main sources of increased baroclinicity.

556 A poleward shift in the factual period of the eddy activity prior to the  
557 storms and of the backward trajectories has been found. According to [Hoskins](#)  
558 [and Hodges \(2019\)](#), in autumn the main North Atlantic storm track is located  
559 farther poleward than in spring. Hence, the poleward shift of the trajectories  
560 could be explained by a higher frequency of storms in autumn, as an indirect  
561 climate change signal. There is also a weak poleward shift of the backward  
562 trajectories in autumn, which acts as a direct climate change signal. However,  
563 we have also found that it is in spring when this poleward shift is greatest. In  
564 addition, the wavier pressure field configuration may act to deflect cyclones  
565 poleward over the North Atlantic. We thus deduce that the poleward shift is  
566 due to a combination of: (i) a direct climate change that shifts poleward the  
567 storms, especially in spring, probably due to a poleward shift of the region  
568 of maximum baroclinicity; (ii) an indirect signal, whereby analogues become  
569 more common in autumn when the cyclones are located further poleward; and  
570 (iii) wavier pressure patterns that deflect cyclones. Further analysis must be  
571 performed to evaluate each components' contribution to the observed poleward  
572 shift of the cyclones. A future pathway could be to create analogues based on  
573 the cyclone tracks.

574 Finally, an increase in precipitation in Northern Italy has been detected  
575 in the factual period, along with an increase in low-level temperature in the  
576 same region and wind gust over the Alps, Liguria and Provence. This result is  
577 in agreement with [Reale et al \(2022\)](#) and [Zappa et al \(2015\)](#), who, using cli-  
578 mate models, found that the cyclone-related precipitation rate and wind speed  
579 will increase in the central Mediterranean region in a warmer climate. The  
580 increase in precipitation in Northern Italy could have a thermodynamic origin,  
581 linked to temperature by the Clausius Clapeyron relation, and a dynamic ori-  
582 gin, related to the meridional wind and the orographically induced Stau effect.  
583 Deseasonalized temperature differences show that the temperature signal cor-  
584 responds mainly to a seasonal shift of the analogues, which suggests that the  
585 increase in precipitation could be related to the shift from spring to autumn  
586 cyclones. Hence, in a warmer climate, hazardous Alex-like storms may become  
587 more likely, as they occur more frequently in the fall when the Mediterranean  
588 is warmer and the air is moister than in spring. The increase in southerly  
589 advection by 10m meridional wind has a dynamic origin, as storms have lower  
590 core pressures at *lag +12* dates in the factual climate. Southerly winds advect  
591 humid air from the Mediterranean, and together with the orographic forcing  
592 by the Alps, can increase precipitation. Hence, given the differences observed  
593 in the surface fields, more flooding could be triggered at the base of the Alps,  
594 the region that suffered the largest impacts during the Alex.

595 To summarize, our results show a more persistent atmospheric pattern for  
596 Alex-like cyclones in a warmer climate. Both signals indicate that the cyclones  
597 remain over the same region for longer, favouring extreme events that result  
598 from prolonged weather conditions. There is also an increase in the maxi-  
599 mum eddy kinetic energy during their development and the cyclones display  
600 lower pressures during their decay phase. In addition, in the factual period,

Alex's analogues produce more precipitation in Northern Italy, and specifically along the southward flank of the Alps, which could trigger more severe flooding events. We emphasize that our findings do not explicitly demonstrate that the observed changes are entirely anthropogenically-driven, and they may also be influenced by the internal variability of the climate system. A large sample of model data would be required to adequately isolate the impact of anthropogenic radiative forcing.

The approach used in this work to attribute storm Alex and its impacts to climate change combines several techniques, including the analogues method (Yiou, 2014), dynamical systems theory (Faranda et al, 2017), and extreme event attribution (Stott et al, 2016), to provide a novel, complete toolkit for attribution studies. This toolkit may be applied with profit to other severe extra-tropical and tropical cyclones, and provide new insights on the influence of climate change on extreme weather phenomena.

## Statements and declarations

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- Ethics approval: Not applicable.
- Consent to participate: Not applicable.
- Consent for publication: Not applicable.
- Availability of data and materials: ERA5 data are available on the C3S Climate Data Store at <https://cds.climate.copernicus.eu/#!/home>.
- Code availability: The main results of this work were obtained using Python. The scripts are available upon request.
- Authors' contributions: MG performed the analysis. MG and DF co-designed the analyses. All authors participated to drafting and reviewing the manuscript.

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## 915 **Appendix A Local dimension $d$ and** 916 **persistence $\theta^{-1}$**

917 Local dimension  $d$  is computed by applying extreme value statistics to Poincaré  
 918 recurrences of a state  $\zeta$  (Lucarini et al, 2016).  $\zeta$ , here represented by Alex’s  
 919 longitude-latitude sea-level pressure map, is a reference point in an appro-  
 920 priately defined phase space. Here, the trajectories in this phase space are  
 921 successions of 6-hourly sea-level pressure maps in a similar fashion as described  
 922 in Faranda et al (2017). We then compute the probability that the trajectory  
 923 returns close to  $\zeta$ , namely within a ball of radius  $\epsilon$  centered on  $\zeta$ . This prob-  
 924 ability has been studied first by Freitas et al (2008) and obeys an extreme  
 925 value distribution. In order to compute this probability, we first calculate the  
 926 distances between  $\zeta$  and all other points within our dataset as:

$$g(x(t)) = -\log(\text{dist}(x(t), \zeta)) \quad (\text{A1})$$

927 where  $\text{dist}(x(t), \zeta)$  is the Euclidean distance of SLP maps between each  
 928 timestep  $x(t)$  and  $\zeta$ . The Freitas-Freitas-Todd theorem (Freitas et al, 2008),  
 929 modified by (Lucarini et al, 2012), states that the probability of recurrences,  
 930 namely of  $x(t)$  to fall inside a ball of radius  $\epsilon$  and centered at  $\zeta$ , converges to  
 931 a Generalized Pareto Distribution:

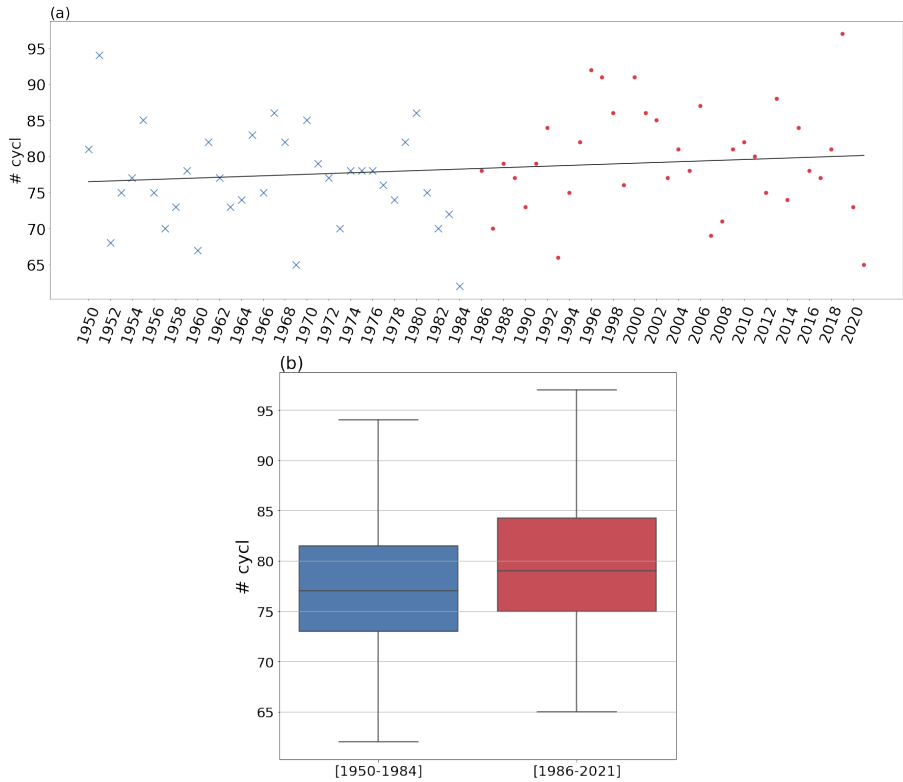
$$P(z > s(q)) \simeq \exp[-\vartheta(\zeta) \frac{z - \mu(\zeta)}{\sigma(\zeta)}] \quad (\text{A2})$$

932 where  $z = g(x(t))$ . The radius  $\epsilon$  is related to a threshold  $s(q)$  of the time  
 933 series of the distances computed as Eq. (A1) by  $\epsilon = e^{-s(q)}$ . Due to the appli-  
 934 cation of the  $-\log$ , the exceedances of the threshold are the points that fall  
 935 within the radius  $\epsilon$  from  $\zeta$ . In this work we take  $q$  as the 99th percentile of  
 936 our distance timeseries, so that 1% of the distances exceed the threshold (Fig.  
 937 B13). The local dimension  $d$  is obtained as:  $\sigma = 1/d(\zeta)$ .

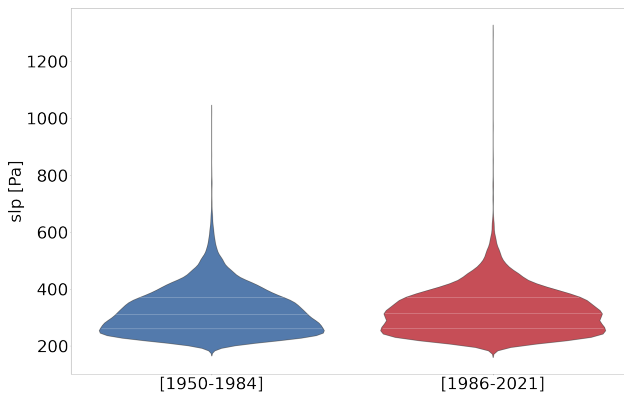
938 We fit a Generalized Pareto Distribution to the exceedances using the  
939 Maximum Likelihood estimator. We also have tested two other methods, the  
940 Method of Moments and L-moments, and we have found similar results, namely  
941 that when the differences between  $d$  in factual and counterfactual periods are  
942 statistically significant for a method, they also are so for the others (Fig. B14).

943 The extremal index  $\vartheta$  is an adimensional parameter between 0 and 1. Its  
944 inverse can be interpreted as the mean residence time of phase-space trajecto-  
945 ries within a radius  $\epsilon$  around  $\zeta$  in units of the timestep of the data being used,  
946 namely a measure of persistence  $\theta$ . We compute  $\vartheta$  using the [Süveges \(2007\)](#)  
947 estimator.

## 948 **Appendix B Additional figures**

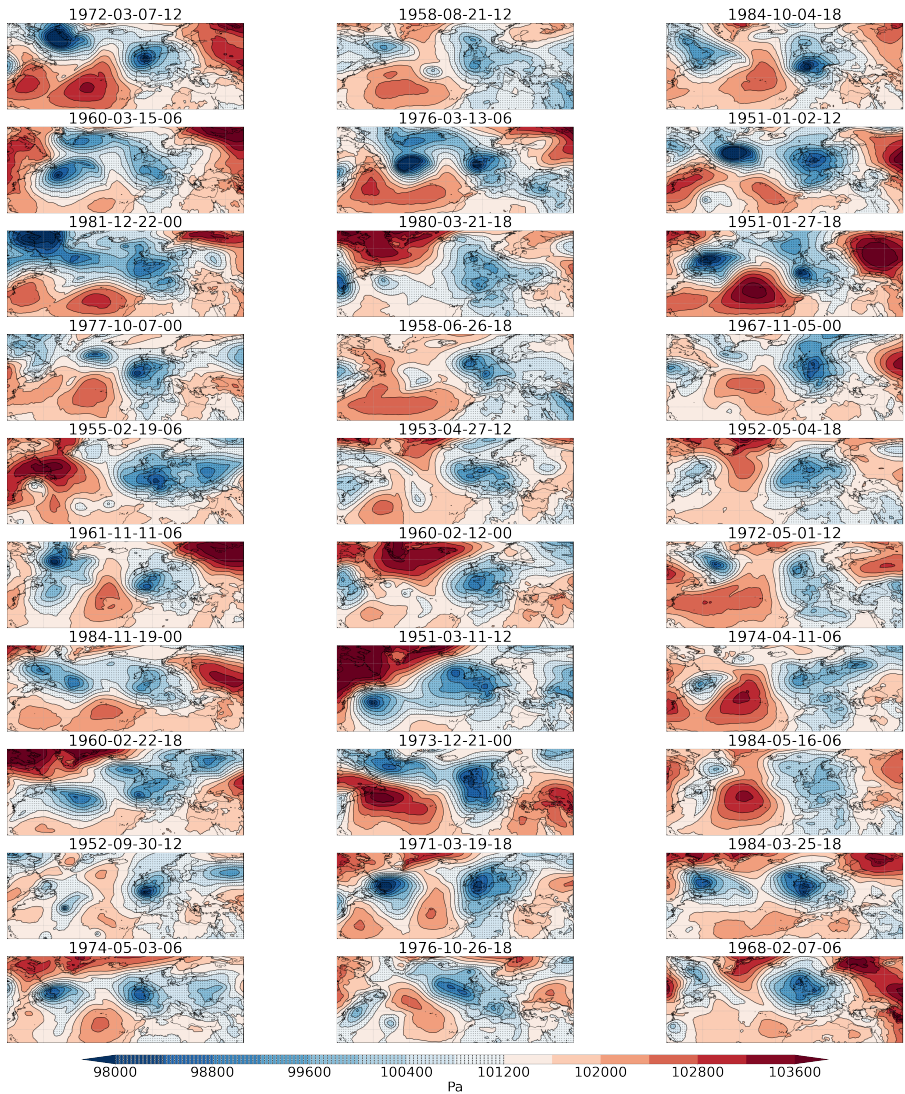


**Fig. B1** (a) Number of cyclones over the North Atlantic and western Europe (60W–20E, 30–65N) per year for counterfactual (blue crosses) and factual (brown dots) periods and trend considering the whole period (black line). Cyclones are tracked using the *TempestExtremes* software by Ullrich et al (2021); Ullrich and Zarzycki (2017) using ERA5 data. The customized algorithms in *DetectNodes* and *StitchNodes* codes are almost the same as in Ullrich et al (2021). Cyclones are required to have a closed contour of 2hPa within  $6^\circ$  of the cyclone center, and those with their centers within  $6^\circ$  of one another are merged (*DetectNodes*). Cyclones must persist for at least 60 hours, with a maximum gap of detection of 18 hours, and they must move  $12^\circ$  great-circle distance from the start to the end of the trajectory (*StitchNodes*). (b) Probability distributions of the number of cyclones. The difference in the probability distributions has been tested using the Wilcoxon Rank-Sum test, where the null hypothesis is that the two distributions have equal medians at the 5% significance level, and the alternative hypothesis is that the distribution underlying the factual period is greater than the distribution underlying the counterfactual period. The *p-value* is 0.039, indicating that the median of the factual period is significantly greater than that of the counterfactual period.

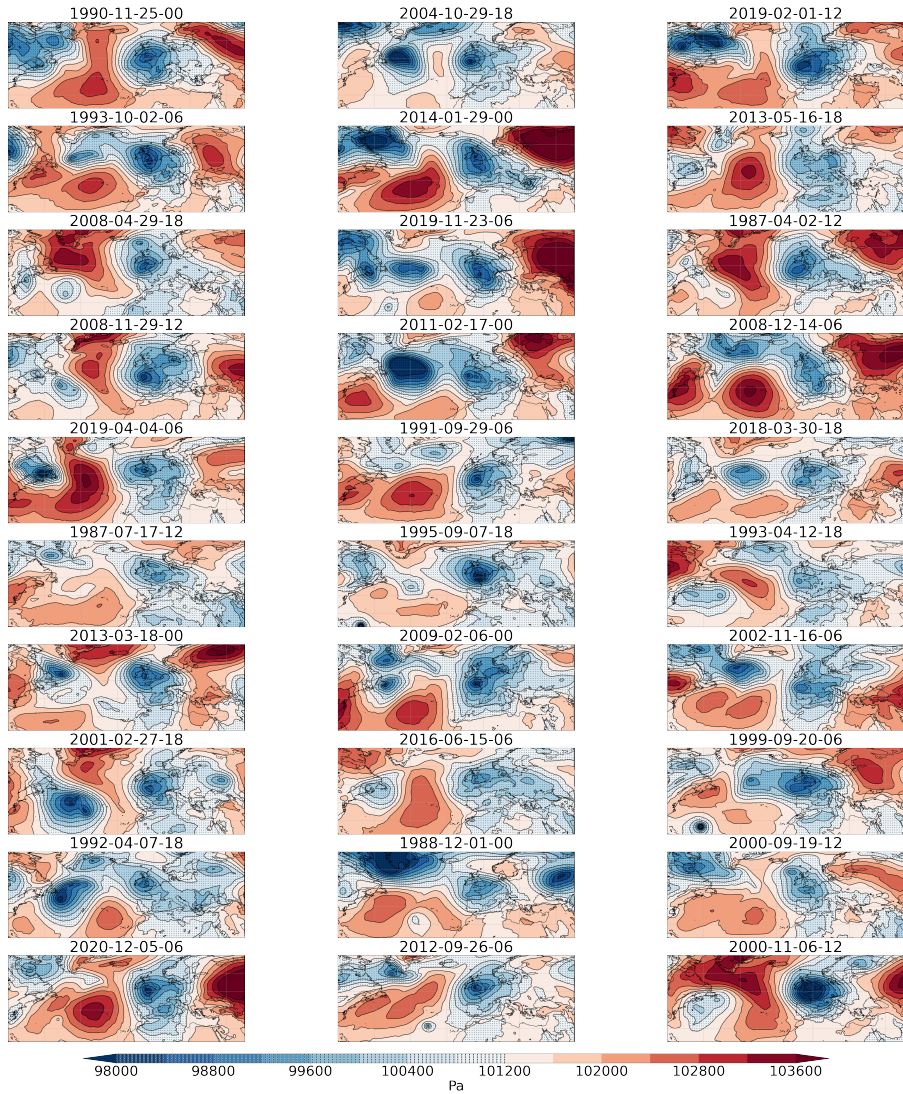


**Fig. B2** Probability distribution of the average Euclidean distance between the sea level pressure map of every time step and its 30 closest analogues. The statistical significance of the difference between the distributions is assessed using a two-sample Kolmogorov-Smirnov test with a 5% significance level. No significant differences between the two periods are found.

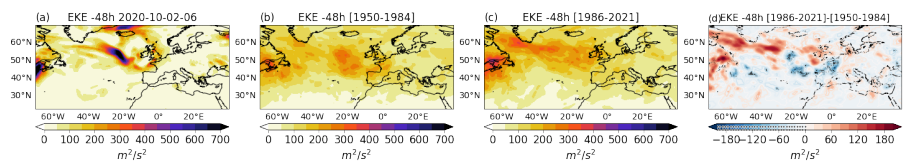




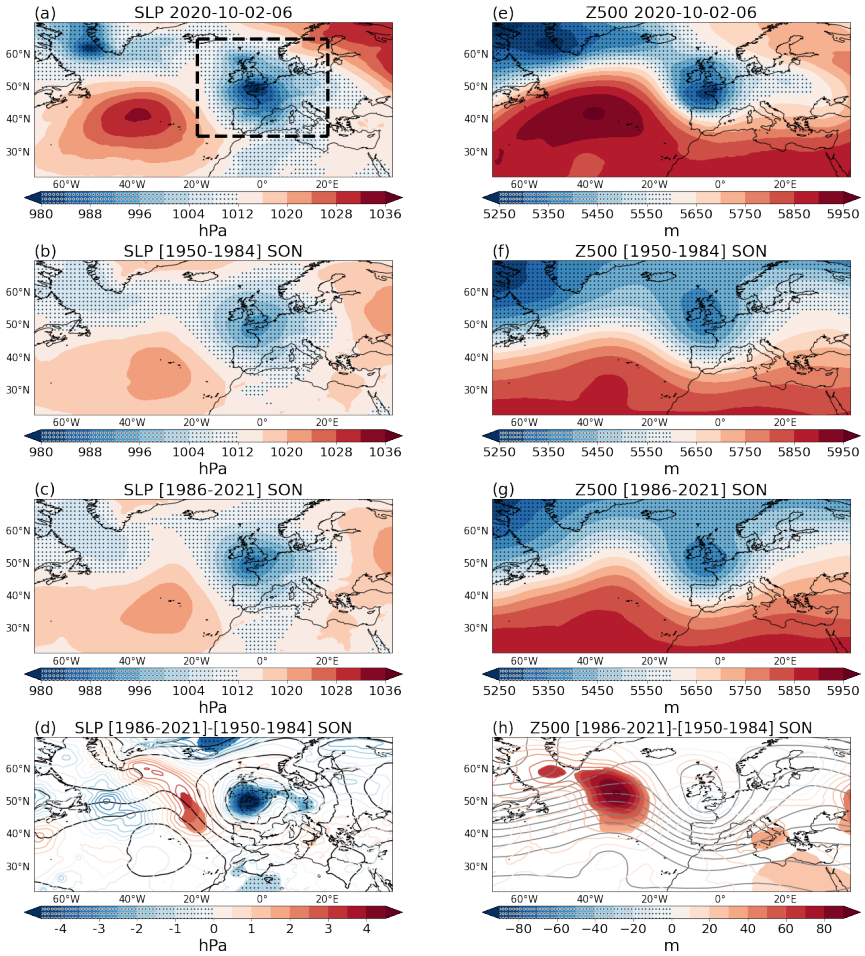
**Fig. B3** Mean sea-level pressure of the 30 analogues of cyclone Alex in the counterfactual period.



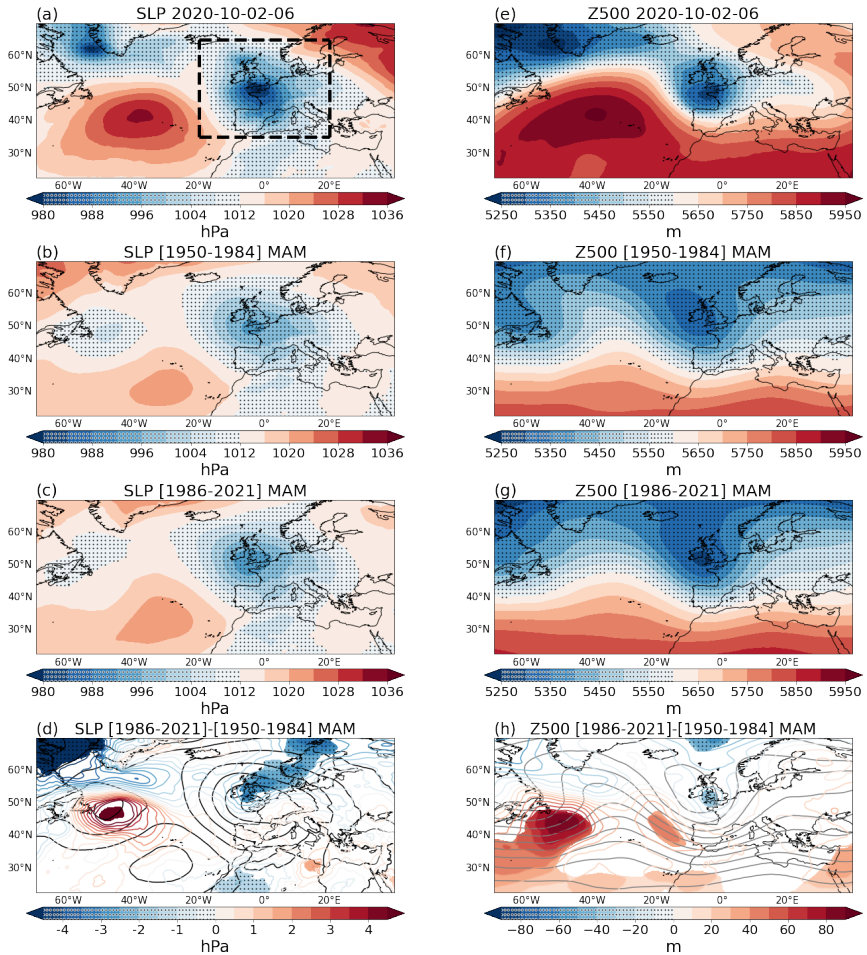
**Fig. B4** Mean sea-level pressure of the 30 analogues of cyclone Alex in the factual period.



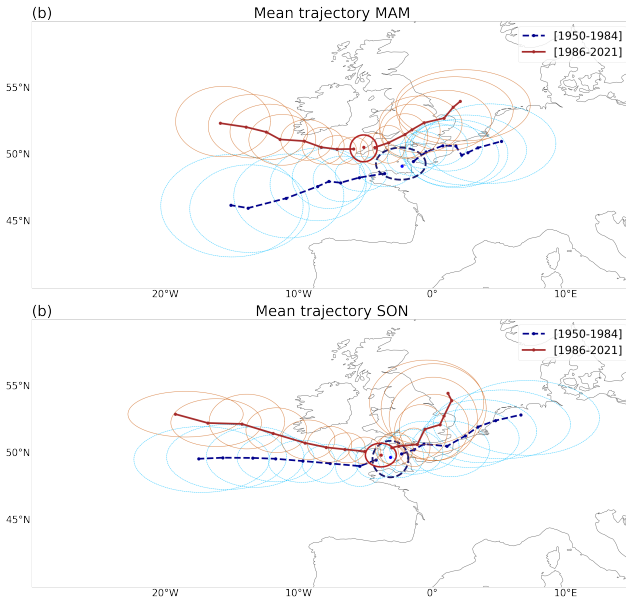
**Fig. B5** Same as Fig. 2 (i–l) but for eddy kinetic energy centered 48 hours before Alex's lag 0 date (a) and analogue lag 0 dates (b–d).



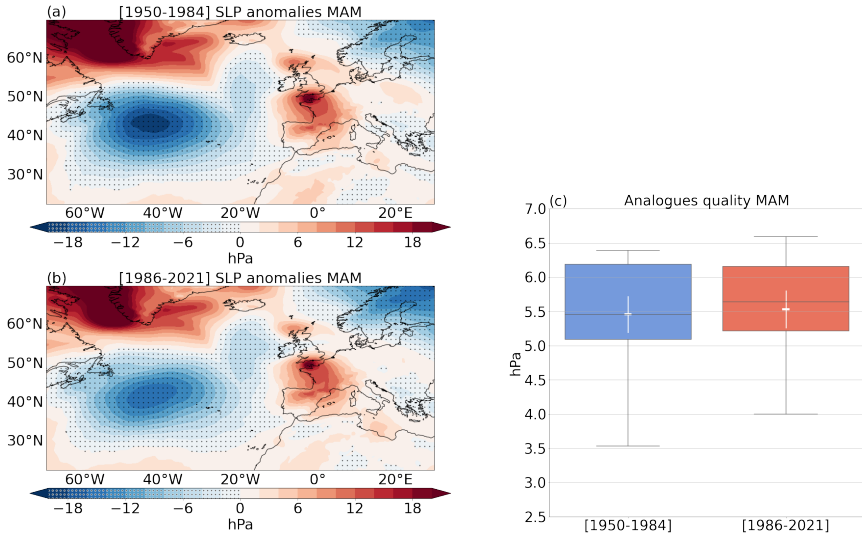
**Fig. B6** Same as Fig. 2 (a–h) but for autumn (September–October–November) analogues



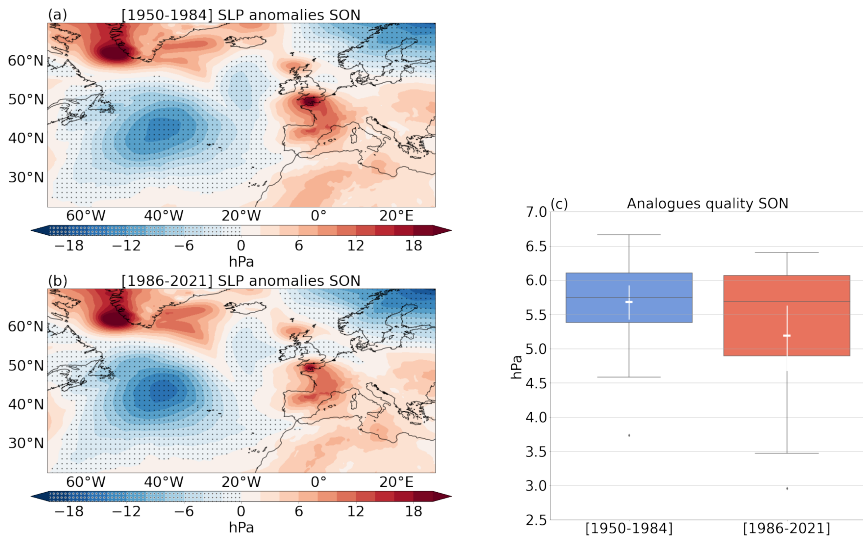
**Fig. B7** Same as Fig. 2 (a-h) but for spring (March-April-May) analogues



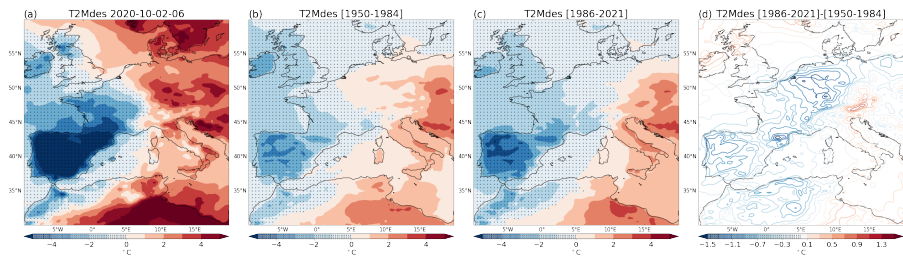
**Fig. B8** Same as Fig. 4 but for (a) spring (March-April-May) analogues and (b) autumn (September-October-November) analogues.



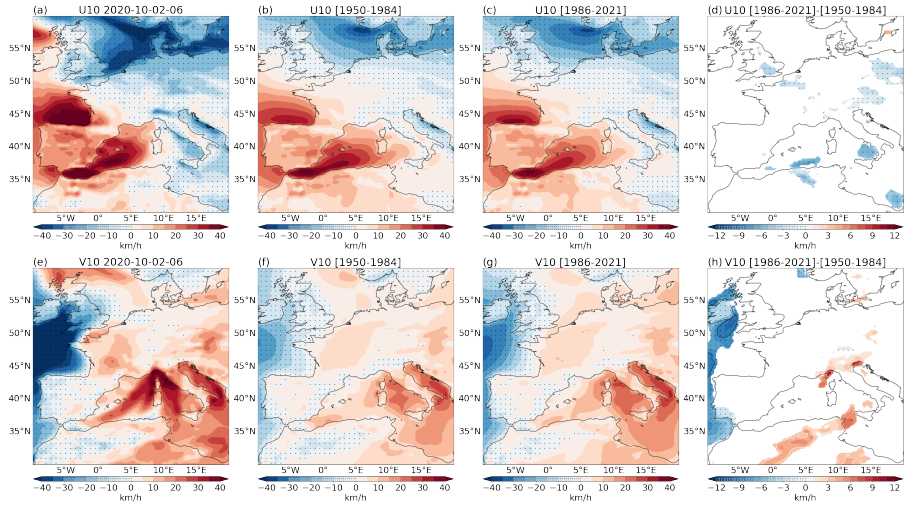
**Fig. B9** Same as Fig. 6 but for spring (March-April-May) analogues



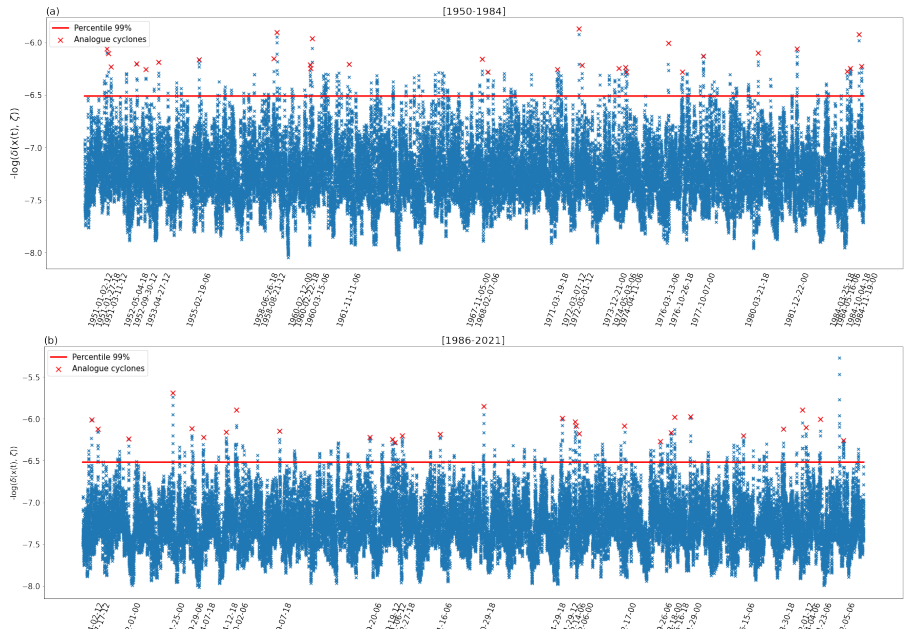
**Fig. B10** Same as Fig. 6 (a–h) but for autumn (September–October–November) analogues



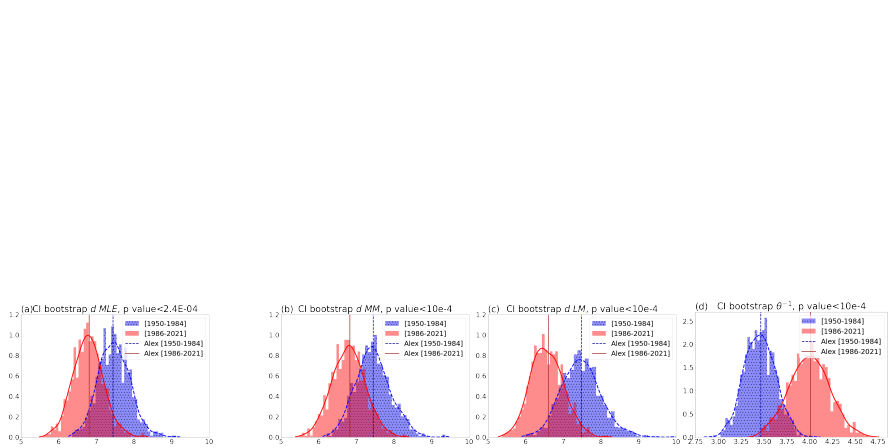
**Fig. B11** 24-hour means of deseasonalized 2-meter air temperature of Alex (a), counterfactual analogues (b), factual analogues (c) and differences between the analogues in the two periods (d). The start times to compute the temporal mean are the *lag 0* dates and end times are 24 hours after them.



**Fig. B12** 24-hour means of 10m zonal wind (first row) and 10m meridional wind (second row) for Alex (a, e), counterfactual analogues (b, f), factual analogues (c, g), and difference between the analogues in the two periods (d, h). The start times to compute the temporal means are the *lag 0* dates and end times are 24 hours after them.



**Fig. B13** Timeseries of the  $g(x(t))$  distances between Alex and all the other timesteps in the counterfactual (a) and factual (b) periods. Red crosses show the analogue cyclones. *lag 0* dates are indicated on the x-axis. Red lines show the 99% quantile  $s(q)$ , and the exceedances are used to compute the dynamical system metrics.



**Fig. B14** Bootstrap distribution for local dimension  $d$  computed using Maximum Likelihood Estimation (a), Method of Moments (b), and L-Moments (c), and for persistence  $\theta^{-1}$ . The confidence interval is the middle 95% bootstrap distribution. The statistical significance of the difference between factual and counterfactual distributions has been assessed using the Kolmogorov-Smirnov test. P-values are shown in the panel titles, indicating that all the distributions are significantly different at the 5% level.