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Changes in synoptic circulations associated with documented derechos over France in the past 70 years

Lucas Fery[1,2,*] and Davide Faranda[1,3,4,*]

[1]Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ, Université Paris-Saclay, IPSL, 91191 Gif-sur-Yvette, France
[2]SPEC, CEA, CNRS, Université Paris-Saclay, F-91191 CEA Saclay, Gif-sur-Yvette, France
[3]London Mathematical Laboratory, 8 Margravine Gardens London, W6 8RH, UK
[4]Laboratoire de Météorologie Dynamique/IPSL, École Normale Supérieure, PSL Research University, Sorbonne Université, École Polytechnique, IP Paris, CNRS, Paris, 75005, France
[*]These authors contributed equally to this work.

Correspondence: Lucas Fery (lucas.fery@lsce.ipsl.fr)

Abstract. Derechos are a type of severe windstorm characterized by a swath of wind damage several hundred kilometers long. They are known to cause widespread damage and can have a significant impact on human safety and infrastructure. A recent example is the European derecho of 18 August 2022 that produced damaging surface wind gusts (>200 km/h) and affected Corsica, Italy and Austria within 12 hours. The goal of this paper is to analyse recent derechos in France in the satellite era and assess the role of climate change in modifying their characteristics. We identify eleven (11) events in the past and provide their tracks retrieved using the ERA5 reanalysis dataset. To detect climate change signal, we compare cyclonic atmospheric circulations (low pressure systems) that can lead to derechos in the distant past (1950-1979), when warming was just beginning, and in the recent past (1993-2022). Two of the events are found to be unprecedented, that is no good analogues can be found in at least one period and attribution statements cannot be made on the basis of the present analysis. For most of the other events, instead, we find a significant signal of increased precipitation in the recent period which, without change in circulation, is explained by higher temperatures. For these events there is also not a clear change in depth of the low pressure system trigger. Finally, we can exclude the role of climate variability of El Nino (ENSO) in most of the events, while we cannot rule out the influence of the Atlantic Multidecadal Oscillation (AMO) in favoring low pressure systems possibly leading to derechos.

1 Introduction

The term "derecho" is used to describe thunderstorm episodes that are characterized by a particularly long-lasting, strong and widespread production of downbursts. These serial downburst episodes can only constitute a derecho if they are generated by an extratropical mesoscale convective system (MCS), which excludes cyclones with tropical characteristics. The associated radar signatures generally have linear characteristics, with bow echoes. It is not uncommon to observe line echo wave pattern signatures during derechos (development of an undulation of the main precipitating area, then a bulge associated with a meso-depression).

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To meet the criteria for a derecho, the MCS must fulfill a series of characteristics defined by Fujita and Wakimoto (1981) and later by Johns and Hirt (1987), namely: i) wind-gusts of convective nature with a speed greater than or equal to 90 km/h or – when wind-speed measurements are not available – the presence of a concentrated area of damage following downbursts; ii) this zone of strong convective winds must extend over an area whose major axis exceeds 400 km; iii) the convective gusts must have an identifiable spatio-temporal progression, iv) at least 3 gusts greater than or equal to 120 km/h must be measured or assessed on the basis of damage within the area covered by the episode, v) these 3 gusts must be separated by at least 64 km from each other, vi) there must be no interruption of more than 3 hours between two convective gusts of more than 90 km/h. As we can see, the criteria that define a derecho are precise and very restrictive. Therefore, only a few derechos are registered each year in the world.

The derechos are phenomena that are better documented in the great plains of the United States, in flat areas where the available energy is important and, more rarely, at sea (Ashley and Mote, 2005; Gatzen et al., 2020). For these reasons, the public opinion was shocked by the violence and the widespread destruction of the derecho which hit Corsica in summer 2022: this MCS formed during the night of August 17 to 18 over the northern Balearic Islands, moved rapidly to the northeast, affecting Corsica in the early morning. An initial line of thunderstorms gradually curved to become a bow echo while the large scale conditions caused the movement of the cut-off low associated with the storm towards the east. The system was fueled by the extremely hot water of the Mediterranean sea and convection produced intense downbursts with up to 225 km/h surface wind gusts over Corsica. The system then affected central and northern Italy and Austria, within 12 hours. With 12 casualties, over 100 people injured and disruption of electric power lines (Wikipedia, 2022), there was immediate questioning about whether this exceptional storm could be attributed to climate change.

The storm was not the first extreme event of European summer 2022 which was governed, at synoptic meteorological scales, by a high-low pressure meridional dipole: the presence of a persistent cold drop (low pressure) located between Portugal and France, a pattern associated with the so-called Spanish plume (Holley et al., 2014) and an anticyclone over the Mediterranean basin (see Fig. 1). The change in the cold-drop position determined the alternation between heatwave conditions (low pressure center over the Eastern Atlantic or Portugal) and stormy conditions (cold drop over Spain) over France . While the anthropogenically-driven warming of the Mediterranean Sea (with anomalies up to +6°C recorded during the summer with respect to the seasonal values for the period 1990-2020) was largely found guilty for the genesis of summer 2022 organized convective systems, an assessment of the role of human-induced climate-change on the occurrence of the derecho is yet missing. Moreover, it is not clear whether this derecho is unique or other similar events have occurred in France.

Because of their scarcity and the difficulty of simulating mesoscale convective events in global and regional climate models, it is difficult to find climate change statements about derechos and in general about severe thunderstorms. Due to these modelling difficulties, even the IPCC reports does not contain information about the fate of derechos under anthropogenic climate change. Nonetheless, in the AR6 report (IPCC, 2021), we find that there is high confidence that "a warmer climate intensifies very wet and very dry weather events and seasons, but the location and frequency of these events depend on projected changes in regional atmospheric circulation". Particularly for Europe, there is moderate confidence that at 1.5°C of warming, "heavy precipitation and associated flooding are projected to intensify and be more frequent", and low confidence that "large-scale

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conditions conducive to severe convection will tend to increase in the future climate". The lack of clear results about the fate of severe convective storms under anthropogenic climate change, including derechos in the Mediterranean, motivates the analysis presented in this study.

To understand how human-caused climate change may impact the dynamics leading to severe weather events like derechos, we are using a method that looks at patterns of circulation. Although there is no one-to-one correspondence between large scale low pressure systems and the occurrence of derechos, we consider the former as large scale precursors of intense convective events. To investigate this, we are examining changes in synoptic conditions by identifying similarities between large-scale sea-level pressure patterns associated with historical derechos in the past (1950-1979) and the recent past (1993-2022). Our assumption is that the past serves as a hypothetical world where the Earth's climate was not as affected by human activity, and that 30 years is a sufficient period to account for natural variability in atmospheric motions. However, we must also consider long-term variability such as that caused by the Atlantic Multidecadal Oscillation or El Nino-Southern Oscillation. If a direct influence of such low-frequency variability is excluded, then changes in analogues between the two periods we consider are attributed to the climate change signal. We present in Section 1.2 the methodological aspects of this work, introducing the relevant assessment metrics. The Section 2 contains, for each event: (i) a meteorological description of the event and (ii) our attribution analyses. Our conclusions are presented in Section 3.

1.1 Data

We first identify a list of derechos that happened in France from online reports and articles in the literature. In particular, we significantly rely on the reports from the website of Keraunos (accessible at https://www.keraunos.org/), a French consulting firm specialized in the forecasting and management of risks related to storm phenomena. They provide useful information on the impacts of several types of severe convective events, along with analysis of the corresponding weather configuration. In total, we have listed 11 documented derechos that happened over France between 1983 and 2022. These are detailed in Table 1 with their date, the French regions and other countries affected, the selected area and months (extended season) for the analogues analysis, and a source that document the event.

For each event, we reconstruct the trajectories of the MCS by a semi-objective method consisting in tracking the hourly position of the maxima of precipitation and wind gusts within the region of interest and in the time span of the event (selected from the reported impacts of the derechos). The results are presented on Figure 2. We use ERA5 data which is the latest climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the implementation of the EU-funded Copernicus Climate Change Service (C3S). It provides hourly data on atmospheric, land surface and sea state parameters from 1950 to the present. The ERA5 data are available on the C3S Climate Data Store on regular latitude-longitude grids at a horizontal resolution of 0.25°×0.25° (Hersbach et al., 2018). Our choice of using ERA5 data for this study is firstly motivated by the consistency of the dataset through a long period of time (73 years) which enables the possibility of detecting changes in the large dynamics. Moreover, the global nature of this datasets allow to avoid the problems of mixing data-sets from different national weather services and ensures a uniform spatial and temporal coverage. Other observational or reanalyses datasets have been considerd but discarded because they do not cover sea-points (e.g. E-OBS) or because of

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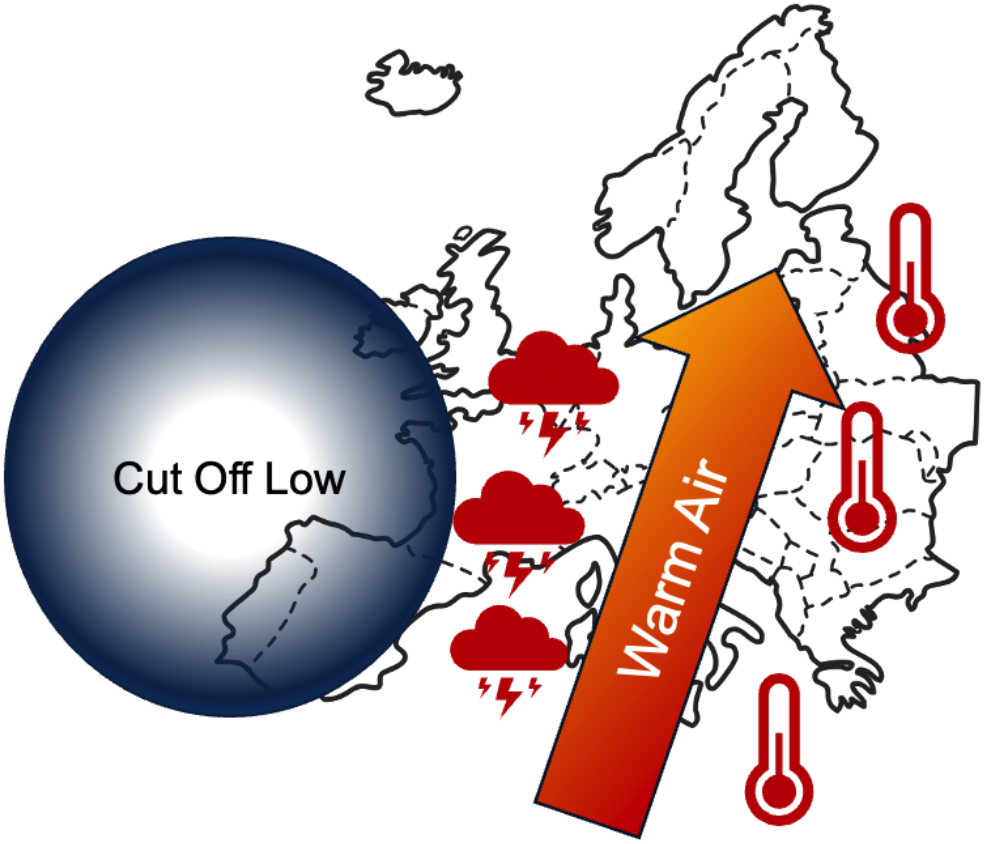

Figure 1. Schematic representation of a typical atmospheric circulation leading to severe thunderstorms over France, as the derecho of August 2022. A cut-off low is a cyclonic circulation detached from the zonal flow and the polar vortex.

the unsufficient temporal and spatial resolutions (e.g. MERRA, NCEP or CFSR). Our methodological and dataset choice thus introduce strong limitations to our analysis:

- Tracking problems: a derecho is an extended MCS and therefore it can have simultaneously more than one active convective cells. Therefore our selection based on maxima of precipitation and wind-gusts only relate to the most intense cell disregarding the frontal or multi cellular structure.

- Confounding elements: on the selected region, we can potentially have maxima of precipitation or wind gusts which correspond to other convective systems or due to orographic effects which will be mistakenly identified as the derecho track. This could be tackled with a more sophisticated tracking algorithm.

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Date	Tracking time span	Affected French regions	Other affected countries	Analogues box	Analogues months	Source
25, 26-07-1983	17:00Z (25-07) to 06:00Z (26-07)	Nouvelle-Aquitaine, Pays de la Loire, Centre-Val de Loire		[5°W–7°E,42°N–48°N]	JJAS	Keraunos (2013a)
17-08-2003	07:00Z to 15:00Z	Occitanie, Provence-Alpes-Côte d'Azur	Spain	[7°W–5°E,40°N–48°N]	JJAS	López (2007)
12-07-2010	06:00Z to 15:00Z	Bourgogne-Franche-Comté, Grand-Est, Centre	Benelux, Germany, Denmark	[5°W–7°E,43°N–50°N]	JJAS	Keraunos (2010)
26, 27-07-2013	21:00Z (26-07) to 06:00Z (27-07)	Nouvelle-Aquitaine, Centre-Val de Loire		[5°W–7°E,43°N–50°N]	JJAS	Keraunos (2013b)
03-01-2014	13:00Z to 22:00Z	Normandie, Hauts-de-France	Belgium, Netherlands, Germany	[5°W-15°E,47°N-59°N]	DJFM	Mathias et al. (2019)
25-01-2014	13:00Z to 22:00Z	Hauts-de-France	United-Kingdom, Belgium, Netherlands	[5°W-10°E,47°N-59°N]	DJFM	Keraunos (2014b)
08-08-2014	15:00Z to 23:00Z	Nouvelle-Aquitaine, Occitanie		[8°W-7°E,40°N-50°N]	JJAS	Keraunos (2014a)
16-09-2015	13:00Z to 17:00Z	Bourgogne-Franche-Comté, Grand Est	Benelux	[8°W-7°E,40°N-50°N]	JJAS	Keraunos (2015)
02-03-2016	11:00Z to 17:00Z	Hauts-de-France, Normandie, Pays de la Loire, île-de-France, Centre-Val de Loire		[8°W-7°E,40°N-50°N]	DJFM	Keraunos (2016)
29-04-2018	14:00Z to 18:00Z	Bourgogne-Franche-Comté, Grand Est	Belgium	[8°W-7°E,40°N-50°N]	MAMJ	Keraunos (2018)
18-08-2022	07:00Z to 17:00Z	Corse	Italy, Slovenia, Austria, Czech Republic	[5°W-20°E,35°N-50°N]	JJAS	ESSL (2022)

Table 1. Documented derechos over France with the tracking time span, the affected regions and countries, the specification used for the analogues computations (area and months) and a reference for the reported events.

– Dataset problems: ERA5 is not ideal for studying convective events as the values of precipitation and wind gusts correspond to averages over the rather low resolution grid (with a typical dimension of 20 – 30 km) and these variables are estimated using the output of parameterized models and not directly from observations.

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All these problems could be partially address either by using more sophisticated tracking algorithms or by using more reliable data from radar or stations observations as done e.g. by López (2007), Hamid (2012) and Mathias et al. (2019). Consequently, the trajectories showed on Figure 2 are only meant to illustrate qualitatively the paths of the most intense core of the derechos and to identify the area to be used for the analogues search. While in most cases, the trajectories are consistent with a chronological progression along a straight line, some reconstructions are erratic as for the derecho of August 17, 2003 represented on Figure 2b), especially for the tracking of maximum precipitation, due to the limitations cited above.

1.2 Methods

We compare the 1993-2022 sea level air pressure records to records from 1950-1979, when warming was just beginning. These pressure analogues reflect the large-scale airflows that can drive extreme events such as heat waves, cold waves, large-scale thunderstorms or tornado outbreaks, medicanes, tropical and extratropical cyclones and, in the present case, MCS associated with derechos.

The method ensures that comparisons are relevant, unlike purely statistical modeling techniques, which aim to simply analyze meteorological variables without tracing them back to the phenomena that produce them - a thunderstorm or hurricane, for example. In addition, this method allows us to determine when a weather event is unprecedented because of an atmospheric circulation that has never been observed in the past making it statistically impossible to say whether climate change has made the event more likely.

The attribution protocol described in Faranda et al. (2022) has already been applied and validated for pressure maps leading up to a series of extreme events in the year 2021, including winter storm Filomena, the French spring cold wave, the Westphalian floods, the Mediterranean summer heat wave, Hurricane Ida, the Po Valley tornado, medicane Apollo, and the Scandinavian late fall cold wave. Here we apply it for the first time for the cases of derechos as follows.

We divide the ERA5 data set into two periods: 1950-1979 and 1993-2022 each consisting of 30 years of daily data. We consider the first period to represent a counterfactual world with a weaker anthropogenic influence on climate than the second period, which represents our factual world affected by anthropogenic climate change. Here, we assume that 30 years is a long enough period to average out high-frequency interannual variability of the atmospheric motions. This time period is also recommended by the WMO for the computation of climate normals (Arguez and Vose, 2011). To account for the possible influence of low-frequency modes of natural variability in explaining the differences between the two periods, we also consider the possible roles of the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). The role of ENSO in modulating extreme precipitation events in Europe has been assessed in Nobre et al. (2017) and found to be significant in some regions of the continent. The role of AMO has been discussed, e.g., in Zampieri et al. (2017) who found an influence on pressure, precipitation and temperature patterns.

For each period, we examine all daily averaged sea level pressure (slp) maps and select the best 29 analogues, i.e. the maps minimizing the Euclidean distance to the event map itself. The number of 29 corresponds approximately to the smallest 3‰ Euclidean distances in each subset of our data. We tested the extraction of 25 to 50 analogous maps, without finding qualitatively important differences in our results. For the factual period, as is customary in attribution studies, the event itself

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is suppressed. In addition, we prohibit the search for analogues within a one-week window centered on the date of the event. We also restrict the search for analogues to the extended season in which each event occurs (DJFM, MAMJ, JJAS, or SOND). This allows us to identify possible changes in seasonality between the counterfactual and factual periods, while avoiding confounding the different physical processes that may contribute to a given class of extreme events during warm and cold seasons.

Finally, we examine the seasonality of the analogues during the relevant season and their association with ENSO and AMO. We perform this last analysis using monthly indices from NOAA/ERSSTv5 data and retrieved from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. In particular, the ENSO index is version 3.4 as defined by Huang et al. (2017), and the AMO index is calculated as described in Trenberth and Shea (2006). When the ENSO 3.4 index is positive, it corresponds to El Niño, and when it is negative, it corresponds to La Niña. To assess the possible association of ENSO and AMO on circulation changes between factual and counterfactual periods, we compare the distributions of ENSO and AMO indices for the analogues of the two periods and we evaluate any significance changes between factual and counterfactual distributions by performing a two-tailed Cramér-von Mises test (Anderson, 1962) at the 0.05 significance level. If the p-value is smaller than 0.05, the null hypothesis (H = 0) that both samples are from the same distribution is rejected, and the influence of internal variability (AMO or ENSO) cannot be excluded. All relevant figure panels display the p-value (pval) and the H-test result in the title. Finally, we also compute the best 3‰ analogues for all the 1950-2022 slp dataset, without dividing it into factual and counterfactual periods and estimate a linear trend. Note that for this global quantile the total number of analogues in all decades amounts to 71. We compute the confidence interval of such a trend using the Wald method (Stein and Wald, 1947) in order to assess significance of the trends.

Following Faranda et al. (2022), we define certain quantities that support our interpretation of analogue-based assignment. All these quantities can then be compared between the counterfactual and factual periods.

- **analogue quality Q**: Q is the average Euclidean distance of a given day from its 29 closest analogues. If the value of Q for the extreme event belongs to the same distribution of its analogues then the event is not unprecedented and the attribution can be performed, if the value of Q is greater than those of its analogues the event is unprecedented and therefore not attributable.

- **Predictability Index** D**.** Using dynamical systems theory (Freitas et al., 2011, 2016; Lucarini et al., 2016), we can compute the local dimension D of each slp map (Faranda et al., 2017a, 2019). The local dimension is a proxy for the number of degrees of freedom of the field, meaning that the higher D, the more unpredictable the temporal evolution of the slp maps will be (Faranda et al., 2017b; Messori et al., 2017; Hochman et al., 2019). If the dimension D of the derecho event analyzed is higher or lower than that of its analogues, then the extreme will be respectively less or more predictable than the closest dynamical situations identified in the data.

- **Persistence index** Θ: Another quantity derived from dynamical systems theory is the persistence Θ of a given configuration (Faranda et al., 2017a). Persistence estimates the number of days we are likely to observe a map that is an analogue of the one under consideration (Moloney et al., 2019b). As with Q and D, we compute the two values of persistence for the extreme event in the factual and counterfactual world and the corresponding distributions of the of persistence for the analogues.

- **Seasonality of analogues**: We can count the number of analogues in each month to detect whether there has been a shift in circulation to months earlier or later in the season. This can have strong thermodynamic implications, for example if a circulation leading to large positive temperature anomalies in early spring becomes more frequent later in the season, when average temperatures are much higher.
- **Association with ENSO and AMO**: To account for the effect of natural inter-decadal variability, we analyze the distributions of ENSO and AMO indices corresponding to the analogues of each event in the factual and counterfactual periods. If the null hypothesis that the two distributions do not differ between the two periods is rejected, we cannot rule out that the thermodynamic or dynamical differences in the analogues are partly due to these modes of natural variability, rather than anthropogenic forcing. On the other hand, if the null hypothesis of equal distributions cannot be rejected, the observed changes in the analogues are attributed to human activity.

2 Results

In order to investigate the characteristics of the derechos, we first provide a detailed description of the synoptic conditions associated with each of the 11 events that were detected in this study. This will include information on the large-scale atmospheric circulation patterns, as well as the wind and precipitation recorded at the time of the events. By examining the synoptic conditions of these events, we will gain a better understanding of the dynamics of derecho formation. Then, we will use the attribution framework previously described in this study to examine the potential role of climate change in modifying the characteristics of these events. This will involve comparing the synoptic conditions of the events during the distant past (1950-1979) and the recent past (1993-2022) to detect any potential changes.

2.1 Derecho of August 18, 2022

On August 18, 2022, the synoptic situation featured a cut-off low over France and a surface minimum over Corsica while there was a high pressure system over the Atlantic. As described in section 1, a MCS developed and moved to the northeast, affecting Corsica, Northern Italy, Slovenia, Austria and Czechia within 12 hours, with the production of strong wind gusts, severe hail and heavy rainfall along a 1000 km axis. For a detailed meteorological report, see for example ESSL (2022). The track reconstructed from ERA5 dataset is presented on Figure 2k).

Figure 3 shows the results of the attribution of the synoptic configuration associated with the episode. The domain analyzed is given in 1. The slp field of the event (Figure 3a) has been used for the search of 29 analogues for the counterfactual and factual periods. Their average is displayed respectively in 3b,c). We do not observe significant differences in the pressure field when subtracting counterfactual from factual analogues (Figure 3d). On the contrary, we observe that temperatures (Figure 3e-h) are significantly warmer (Figure 3h) in the recent period, especially over land, including the Mediterranean Sea except

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over the Gulf of Genoa. This provides an increased amount of convective potential energy, through the transport of warm and moist air in the low-level jet. The atmospheric pattern of the factual period is further associated with higher precipitation over Tuscany and lower precipitation over the French and Spanish coasts (Figure 3i-l), consistent with more intense transport of warm, moist air from the southeast. Finally winds (Figure 3m-p) are generally stronger on the coasts of Provence (Mistral wind) and the Thyrrenian casts of central Italy (Libeccio wind). This can contribute to orographic effect over Tuscany increasing the amount of precipitations.

The quality of the analogues (Figure 3q) shows that this circulation is relatively common compared to the rest of the analogues with no changes in the two periods. We do not detect visible changes in predictability D (Figure 3r) but persistence Θ increases in the factual world (Figure 3s) relative to the counterfactual world.

The seasonal occurrence of analogues (Figure 3t) is quite consistent with the months of thunderstorm occurrence in this area, with a maximum during August; however, we observe a general shift toward analogues occurring earlier or later in the season during the factual period, with a decrease in July.

The changes in ENSO (Figure 3u) are not statistically significant while AMO distributions have a significant shift between the two periods (Figure 3v), suggesting a possible role of the inter-decadal variability of the Atlantic Circulation in the occurrence of these patterns. Finally, when computing analogues for the whole period and counting their frequency per decade, we observe a significant increase, leading to about one more event each decade (Figure 3w).

To summarize, our analysis shows that there is no significant change between past and present in the cut-off low dynamics resulting from the best analogues of the Corsica derecho. Nevertheless, the surface temperatures associated with the cut-off lows are higher in the factual period. We find a significant signal of increased precipitation over Tuscany in the current climate which, without change in circulation, can be explained by the very high temperature of the Mediterranean Sea and the increased winds blowing over Tuscany. We can exclude the role of the climatic variability of el Nino (ENSO) but not that of the Atlantic Multidecadal Oscillation (AMO).

2.2 Previous reported derechos over France

In section 2.1, we analyzed changes in temperature, precipitation and wind speed between factual and counterfactual periods using analogues of the synoptic pattern associated with a single derecho storm (that of August 18, 2022). In this section, we consider previous reported derechos over France in order to evaluate whether robust changes of atmospheric observables can be established between the two periods for the different synoptic situations that produced historical derechos. For the subsequent analyses we will refer to appendice figures A1-A10 and only comment on features relevant for our discussion.

2.2.1 26-07-1983

The derecho of July 26, 1983 occurred within a series of three successive convective storms that happened between July 25 and 27, 1983 in a very warm and unstable context. The synoptic configuration corresponded to the so-called Spanish plume, featuring a cut-off low located near the north-western part of Iberian Peninsula and high pressure systems over Central Europe and Scandinavia. This configuration is known to produce severe thunderstorms over Western Europe as it brings warm air from

North Africa to France and England, moisturized at the low levels by its passing over the Mediterranean sea. The storm that originated from south of Navarre (Spain) crossed the Pyrenees and caused widespread damage due to intense precipitation and extreme wind gusts of up to 200 km/h along an axis covering a distance of more than 800 km from southwest to north of France. The track reconstructed from ERA5 dataset is presented on Figure 2a). For a detailed meteorological analysis, see the report of Keraunos (2013a) about this thunderstorms outbreak.

The analogues analysis is presented on Figure A1. We observe no significant change in circulation pattern (a–d) between the two periods. However, there is a increase of temperature (e–h) on France except on the Mediterranean coast. For precipitation (i–l), we observe a slight increase on the west coast of France from Arcachon to Nantes, with a slight decrease inland. The wind speed (m–p) has increased on the western part of Massif Central and offshore the Côte d'Argent. Analogues quality (q) for the event is very low compared to that of the rest of the analogues for the counterfactual period. The event become instead more common in the factual period as the analogues quality get comparable to that of the event. The predictability of the particular event (r) has increased (lower local dimension) but on average, the predictability of the analogues has decreased (higher local dimension). The persistence (s) has increased between the counterfactual and the factual period for both the particular event and its analogues. We observe (t) a shift of analogues toward late summer (August), with a corresponding decrease in July. The change in the distribution of ENSO index (u) is at the limit of significance and we also cannot exclude the influence of AMO (v). Finally, we do not observe any significant trend in the frequency of analogues (w).

2.2.2 17-08-2003

The configuration on August 17, 2003 featured an upper-level trough located over the Iberian Peninsula. The left exit region of the jet produced upper-level divergence over the coast of the province of Castellón, which induced an area of upward vertical motion initiating deep convection. The derecho emanated from a mesoscale convective complex (MCC) and affected an area along an 550 km long axis from the south of Catalonia (Spain) to the north of Provence-Alpes-Côte d'Azur (France) with maximum wind gusts of 180 km/h recorded. The track reconstructed from ERA5 dataset is presented on Figure 2 (b). See López (2007) for a detailed analysis.

The attribution analysis is presented on Figure A2. We do not observe a significant change of circulation (a–d), while there is significant change of temperatures (e–h) with the factual period being much warmer on the whole selected area than the counterfactual period. However, we do not observe a significant change of precipitation (i–l) apart from a slight decrease in some areas of France and Spain. As for wind speed (m–p), we detect a decrease over the Gulf of Lion. The quality of the analogues (q) is good in the two periods. There is no change in predictability (r) or persistence (s). We observe no shifts in the seasonal frequency of analogues (t). Finally, we cannot rule-out neither a role of ENSO (u) nor AMO (v) in accounting for the observed changes. No trends in analogues frequency over time is detected (w)

2.2.3 12-07-2010

The weather configuration of July 12, 2010 displayed a high level trough over the British Isles and high pressures over Central Europe and Scandinavia. Over western France, there were a cold front driven by a low tropopause anomaly. The configuration

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is typical of those leading to warm-season derechos over Germany described by Gatzen et al. (2020). In the upper troposphere, the simultaneous configuration of right entry/left exit of jet stream created strong divergence which leaded to the development of a MCS with characteristics of a mesoscale convective complex (MCC) and a derecho. The storm whose path was more than 1500 km long, started from center-west of France to north of France to finally reach Belgium, Netherlands, Germany and Denmark. Wind gusts up to 130 km/h were recorded by Météo-France. The strong winds and precipitation caused various damage (Keraunos, 2010). The track reconstructed from ERA5 dataset is presented on Figure 2 (c).

The analogues analysis is presented on Figure A3. There is no significant change in the circulation pattern (a–d), however there is a significant increase of temperature (e–h) over the whole area, which is stronger on the continent. We also observe an increase in precipitation (i–l) in the Bay of Biscay and over the mountain ranges (Massif Central, Alps, Jura) except for the Pyrenees for which there is a decrease of precipitation. No significant changes in wind patterns are detected (m–p). The quality of the analogues (q) is good in the two periods. There is no change in predictability (r) or persistence (s). The analogues are becoming more frequent in July and August and less frequent in September (t). On one hand, the difference of ENSO index (u) is not significant, but on the other hand, we cannot exclude the influence of AMO (v). There is an increasing frequency of analogues with time (w).

2.2.4 26,27-07-2013

In the night between July 26 and July 27, 2013, an MCC developed within a fast south/southwest flow, driven by a minimum positioned over the Atlantic. The jet stream was then stretched on a Portugal - England - Denmark axis. The storm initiated near the coast of Aquitaine and moved towards north of France. Strong wind gusts up to 170 km/h were recorded along a 400 km axis (Keraunos, 2013b). The track reconstructed from ERA5 dataset is presented on Figure 2 (d).

The analogues analysis is presented on Figure A4. We observe a slight weakening of the low pressure system located in the English Channel (a–d). The temperature are much warmer in the factual period (e–h), with a significant increase of precipitation on the north-western part of France (i–l), with a concurrent decrease of precipitation on the south-eastern part of France. No significant signals are observed for the wind patterns (m–p). The analogue quality is good for both periods (q). There is no significant change of predictability (r) and persistence (s).

We observe a shift of the number of analogues (t) from the the late (August, September) to the early season (June, July). The influence of ENSO can be excluded (u), but not that of AMO (v) and no trends in analogues frequency are detected (w).

2.2.5 03-01-2014

The synoptic situation on January 3, 2014 was dominated by a deep low-pressure system (core pressure of 949 hPa) over the North Atlantic with the local minimum close to Scotland. The MCS developed in behind an occluded front within a southwesterly flow. The storm passed over France, Benelux and northwest Germany on a path long of about 650km (see Mathias et al. (2019) for a detailed analysis). The track reconstructed from ERA5 dataset is presented on Figure 2 (e).

The analogues analysis is presented on figure A5.

The circulation pattern (a–d) doesn't change much except for a slightly lower pressure on the western coast of England. The temperatures (e–h) are warmer in Scotland, northern France, the Alps, Benelux, northwestern Germany and south of Scandinavia. We observe significant increase of precipitation in Scotland and southern Norway (i–l). As for wind speed, there is a significant increase in the northern part of North Sea and on the Brittany and Normandy (m–p). The analogues quality (q) is common in comparison with that of the other analogues in both periods.There is a detected change in predictability with a decrease of the local dimension (r), while there is no change in persistence (s). The analogues tends to happen later in the season (s), namely more in January and less in December. The change in ENSO is not significant (u). Finally, we cannot exclude the role of AMO (v) and no significant trends in frequency of occurence over time are detected (w)

2.2.6 25-01-2014

On January 25, 2014, there were a NAO+ pattern (positive North-Atlantic Oscillation phase) along with a high pressure over Scandinavia and a relatively low pressure system over central Europe. The progression of an unstable cold front over England, northern France and the Benelux countries, associated with a large trough on the North Sea, led to the development of a mesoscale convective system with derecho characteristics. Wind gusts up to 130 km/h were recorded along a main axis of more than 500 km (Keraunos, 2014b). The track reconstructed from ERA5 dataset is presented on Figure 2f).

The analogues analysis is presented on Figure A6. There is a significant deepening in the slp patterns (a–d) although the cyclonic curvature much more pronounced during the particular event than in the analogues suggesting a poor quality of the analogues. Temperatures are warmer in the factual period over the North Sea, Scotland and Scandinavia (e–h). The precipitation is larger on the western coast (i–l) of Norway and the wind speed has increased over the North Sea in the factual period (m–p). As announced before, the analogue quality (q) is poor for the counterfactual period and slightly better but still poorer than that of most of the other analogues in the factual period. This means there are no good analogues in the past, and there is a significant amount of analogues that occur in the last decade as emphasized in (w). Therefore, this circulation was unprecedented before the 2010s, and the comparison between the two periods may not be meaningful as there are not enough circulation pattern analogues in the counterfactual period. No signficant changes in predictability (r), persistence (s), frequency of occurence per season (t), ENSO (u) and AMO (v) indices are observed.

2.2.7 08-08-2014

This large-scale stormy episode developed within a rapid west/south-west flow, driven by an upper-level minimum located north-west of Ireland. A branch of the jet stream stretched over the near Atlantic to Brittany, and then moved up towards the North Sea. The high altitude flow was strongly diffluent in the southwest of France, positioned in a right entry configuration, leading to the development of a quasi-linear convective system with a line echo wave pattern that moved eastward from Nouvelle-Aquitaine to Occitanie (Keraunos, 2014a). The track reconstructed from ERA5 dataset is presented on Figure 2 (g).

The analogues analysis is presented on Figure A7. We detect a deepening of the low pressure system off the coast of Britanny (a–d). The temperature (e–h) are significantly warmer almost everywhere on the seleted area. There is a significant increase of precipitation (i–l) over the English Channel, the Pyrenees and north-wester part of Massif Central. The wind speed (m–pà has

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increased offshore in the Bay of Biscay but has decreased in the Gulf of Lion and on the coast of Normandy. The analogue quality (q) is good in both periods. The predictability (r) doesn't change but there is an an increase in persistence (s) on average in the factual period. The analogues are getting more frequent in July and less frequent in June and August (t). Finally, the difference in ENSO index (u) is at the limit of significance and we cannot exclude the role of AMO (v). No trends in frequency of occurrence in time have been detected (w).

2.2.8 16-09-2015

On September 16, 2015 a trough associated with a low pressure located over Brittany arrived from the Bay of Biscay over the Atlantic coast of France. The northeast of France was in a left exit region of the jet directed from west-southwest to north-east. Moreover, the low-level of advection of warm and moist air produced instability. In this context, a MCS developed and adopted a line echo wave pattern that affected an area along an axis of 400 km between Nièvres French department and Luxembourg and south-east of Belgium (Keraunos, 2015). The track reconstructed from ERA5 dataset is presented on Figure 2h).

The analysis with the analogues is presented on Figure A8. There is a large discrepancy between the circulation pattern during the event and the average pattern of the best analogues in counterfactual and factual periods (a–d). There are significantly warmer temperatures (e–h) over the Atlantic, the Mediterranean Sea and the Alps. We observe an increase of precipitation (i–l) in the factual period on the Atlantic coast near Bordeaux and north to the coast of Spain and Brittany, while there is decrease of precipitation in southern France and inland of Spain. The wind speed has significantly increased in the Bay of Biscay and in the English Channel (m–p). Therefore, the attribution cannot be performed due to the lack of analogues situations in the extended summer season. We decided to keep the analogues search in summer for this event, for coherence with most of the other events studied. However, we notice that the quality of analogues (q) is very low in both periods suggesting that this event configuration is unprecedented or that this circulation is not typical of summer months. In light of this, the metrics in panels (r-w) cannot be trusted.

2.2.9 02-03-2016

The configuration on March 3, 2016 featured a pressure minimum over the North Sea, near Scotland, with a concurrent strong Azores anticyclone. A secondary cold front associated with a trough approached the French Channel coast. A squall line developed within the front and affected France over a large area along a northwest-southeast axis of over 500 km. Wind gusts up to 140 km/h were recorded (Keraunos, 2016). The track reconstructed from ERA5 dataset is presented on Figure 2i).

Figure A9 presents the attribution analysis. There is no significant change in the circulation pattern (a–d) except a higher pressure in the factual period over western Spain and in the Mediterranean Sea south to Nice. The temperature (e–h) is higher in the factual period on all Spain, the Mediterranean Sea and south of France. There is an increase of precipitation (i–l) over south of France and Brittany. As for wind speed (m–p), it has increased in the factual period over the Atlantic, the north of Spain and Massif Central, while it has decreased over the Gulf of Lion. The analogues quality (q) is good for both periods in comparison with the distribution. Predictability (r) is higher and persistence (s) is lower in the factual period compared to the counterfactual period. There is an observed decrease of analogues in January and increase in the other months of extended

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winter between the counterfactual and factual period (t). In this case, we cannot rule out the influence of ENSO (u) but that of AMO (v). No trends in frequency of occurrence in time have been detected (w).

2.2.10 29-04-2018

The situation on April 29, 2018 featured a minimum on western-central France with high pressure on central-eastern Europe. A MCS developed from Nièvres department and moved along a south-southwest to north-northeast, 450 km long axis until Belgium (Keraunos, 2018). The track reconstructed from ERA5 dataset is presented on Figure 2 (j).

The attribution results are presented on Figure A10. We observe a slight decrease of pressure (a–d) over Spain between the factual and counterfactual period. There is no signal of change in temperature (e–h) except over the Alps. We observe increased precipitation (i–l) over the Pyrenees in the factual period and no changes in wind patterns (m–p). The quality of analogues (q) for the event is good compared to that of its analogues. There is no detected change in predictability (r) or persistence (s) between the two periods. We observe an increase of the occurrences of analogues in the early season with a subsequent decrease in the later season (t). In this case we cannot rule out the influence of ENSO (u) nor that of AMO (v). There seems to be a trend in the frequency (w) of analogues with an increase in frequency over time.

3 Conclusions

In conclusion, the study provides an in-depth analysis of recent derechos in France that occurred during the satellite era. We identified eleven (11) events and provided their reconstructed tracks using the ERA5 reanalysis dataset. We also investigated the potential role of climate change in modifying the characteristics of circulation patterns associated with historical derechos through their analogues. We compared cyclonic atmospheric circulations (low pressure systems) that can lead to derechos in the distant past (1950-1979) and in the recent past (1993-2022). A summary of our findings is reported in Table 2 and it is constructed by a semi-objective analysis of all results presented in this paper. We found that the synoptic patterns associated with 25-01-2014 and 16-09-2015 derechos are unprecedented, namely no good analogues can be found either in the counterfactual or factual periods and attribution statements cannot be made on the basis of the present analysis. For most of the other events, we found a significant signal of increased precipitation in the recent period which, without change in circulation, is explained by the higher temperatures over land and/or over the Bay of Biscay and the Mediterranean Sea. However, there is not a clear change in the depth of the low pressure systems that trigger these events: only one event show more anticyclonic pressure pattern (26, 27-07-2013) while all other events show no changes or a slight deepening of low pressure patterns associated with derechos. Additionally, we examined the influence of climate variability factors such as ENSO and AMO on derechos, and we found that the role of the climate variability of ENSO can be excluded in most of the events, while the influence of the AMO in favoring low pressure systems possibly leading to derechos cannot be ruled out.

It is important to note that this study has some limitations. One limitation is the sample size of derechos, which is limited to only 11 events during the satellite era. A larger sample size would have improved the statistical significance of the results. Additionally, the study is based on reanalysis data, which have limitations in terms of accuracy and spatial resolution. Also, the

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Date	Δ slp	Δ t2m	Δ tp	Δ wspd	Δ Q	Δ d	Δθ	Δ ENSO	Δ AMO	Attributable?
25, 26-07-1983	0	+	N.A.	+	+	+	+	+	+	Yes
17-08-2003	0	+	-	-	-	0	+	+	+	Yes
12-07-2010	0	+	+	0	0	0	0	0	+	Yes
26, 27-07-2013	+	+	+	-	0	0	0	0	+	Yes
03-01-2014	-	+	N.A.	+	0	-	0	0	-	Yes
25-01-2014	-	+	N.A.	+	0	0	0	0	0	No
08-08-2014	-	+	+	N.A.	-	0	+	0	+	Yes
16-09-2015	-	+	N.A.	+	0	0	-	0	+	No
02-03-2016	0	+	+	+	0	-	-	-	0	Yes
29-04-2018	0	0	+	N.A.	0	0	0	+	+	Yes
18-08-2022	0	+	+	+	0	0	-	0	+	Yes

Table 2. Summary of changes determined via a semi-objective analysis of the attribution results. "0" (white) no changes, "+" (rose) [resp. "-" (cyan)] indicates that positive [resp. negative] changes prevail, "N.A." (purple) stands for Not Assigned and indicates that changes show regional dependencies. The last column indicate if the analogues quality Q is judged sufficient enough to perform attribution.

study only focused on France and the results may not be extended to other regions. The study also does not take into account the potential impact of land use and land cover changes, as well as other surface variables on the derecho formation. Furthermore, the study does not provide a clear explanation for the unprecedented events, and more research is needed to understand the dynamics of these events.

Based on the results and the limitations of this study, it is clear that further research is needed to better understand the dynamics of derechos and their potential link to climate change. One area of focus could be increasing the sample size of derechos, e.g. by including data from different countries, to improve the statistical significance of the results. Another area of focus could be gathering more detailed observations and data on the characteristics of the low pressure systems that trigger derechos, to better understand the dynamics of these systems. High-resolution reanalyses such as the forthcoming ERA6 or the analyses provided by non-hydrostatic convection permitting (Coppola et al., 2021) weather models such as WRF, ICON or AROME could also provide valuable insights on the behavior of derechos and their potential link to climate change. Unfortunately we do not dispose of sufficiently long time series to use the existing data for the purpose of attribution explored in this study. Research could also investigate the role of other climate variability factors such as the Arctic Oscillation and North Atlantic Oscillation (Hurrell et al., 2003) in the formation of derechos. These factors may play a role in modulating the large-scale atmospheric circulation patterns that can lead to derecho formation. The potential impact of climate change on the frequency and intensity of derechos in specific regions and the potential impact on society, infrastructure, and human safety is another area of interest. The link between derechos and other extreme weather events such as flash floods and heatwaves could also be studied to gain insights into the potential impact of derechos on society. Future research could also investigate the impact of

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land use and land cover changes on derecho formation, as well as the role of soil moisture and other surface variables in the formation of derechos.

Code availability. The code to compute the dynamical indicators of predictability D and persistence Θ is available at https://fr.mathworks.com/matlabcentral/fileexchange/95768-attractor-local-dimension-and-local-persistence-computation

Data availability. ERA5 is the latest climate reanalysis being produced by ECMWF as part of implementing the EU-funded Copernicus Climate Change Service (C3S), providing hourly data on atmospheric, land-surface and sea-state parameters together with estimates of uncertainty from 1979 to present day. ERA5 data for tracking are available on the C3S Climate Data Store on regular latitude-longitude grids at 0.25° x 0.25° resolution have been downloaded from https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset, accessed on 2022-10-30. The ERA5 data for attribution have been downloaded from the preprocessed http://climexp.knmi.nl

Appendix A: Predictability and Persistence Indices

The attractor of a dynamical system is a geometric object defined in the space hosting all the possible states of the system (phase-space). Each point ζ on the attractor can be characterized by two dynamical indicators: the local dimension D, which indicates the number of degrees of freedom active locally around ζ, and the persistence Θ, a measure of the mean residence time of the system around ζ (Faranda et al., 2017b). To determine D, we exploit recent results from the application of extreme value theory to Poincaré recurrences in dynamical systems. This approach considers long trajectories of a system — in our case successions of daily SLP latitude–longitude maps — corresponding to a sequence of states on the attractor. For a given point ζ in phase space (e.g., a given SLP map), we compute the probability that the system returns within a ball of radius ϵ centered on the point ζ. The Freitas et al. (2010) theorem, modified by Lucarini et al. (2012), states that logarithmic returns:

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

yield a probability distribution such that:

$$\Pr(z > s(q)) \simeq \exp\left[-\vartheta(\zeta)\left(\frac{z-\mu(\zeta)}{\sigma(\zeta)}\right)\right] \tag{A2}$$

where $z = g(x(t))$ and s is a high threshold associated to a quantile q of the series $g(x(t))$. Requiring that the orbit falls within a ball of radius ϵ around the point ζ is equivalent to asking that the series $g(x(t))$ is over the threshold s; therefore, the ball radius ϵ is simply $e^{-s(q)}$. The resulting distribution is the exponential member of the Generalized Pareto Distribution family. The parameters μ and σ, namely the location and the scale parameter of the distribution, depend on the point ζ in phase

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space. $\mu(\zeta)$ corresponds to the threshold $s(q)$ while the local dimension $D(\zeta)$ can be obtained via the relation $\sigma = 1/D(\zeta)$. This is the metric of predictability introduced in Section 1.2.

When $x(t)$ contains all the variables of the system, the estimation of D based on extreme value theory has a number of advantages over traditional methods (e.g. the box counting algorithm (Liebovitch and Toth, 1989; Sarkar and Chaudhuri, 1994)). First, it does not require to estimate the volume of different sets in scale-space: the selection of $s(q)$ based on the quantile provides a selection of different scales s which depends on the recurrence rate around the point ζ. Moreover, it does not require the a priori selection of the maximum embedding dimension as the observable g is always a univariate time-series.

The persistence of the state ζ is measured via the extremal index $0 < \vartheta(\zeta) < 1$, an adimensional parameter, from which we extract $\Theta(\zeta) = \Delta t/\vartheta(\zeta)$. Here, Δt is the timestep of the dataset being analysed. $\Theta(\zeta)$ is therefore the average residence time of trajectories around ζ, namely the metric of persistence introduced in Section 1.2, and it has unit of a time (in this study days). If ζ is a fixed point of the attractor, then $\Theta(\zeta) = \infty$. For a trajectory that leaves the neighborhood of ζ at the next time iteration, $\Theta = 1$. To estimate ϑ, we adopt the Süveges estimator (Süveges, 2007). For further details on the the extremal index, see Moloney et al. (2019a).

Author contributions.

LF performed the detection and tracking of the events. DF performed the attribution analyses. Both authors contributed to discuss the results and write the manuscript.

Competing interests. The authors declare no competing interests

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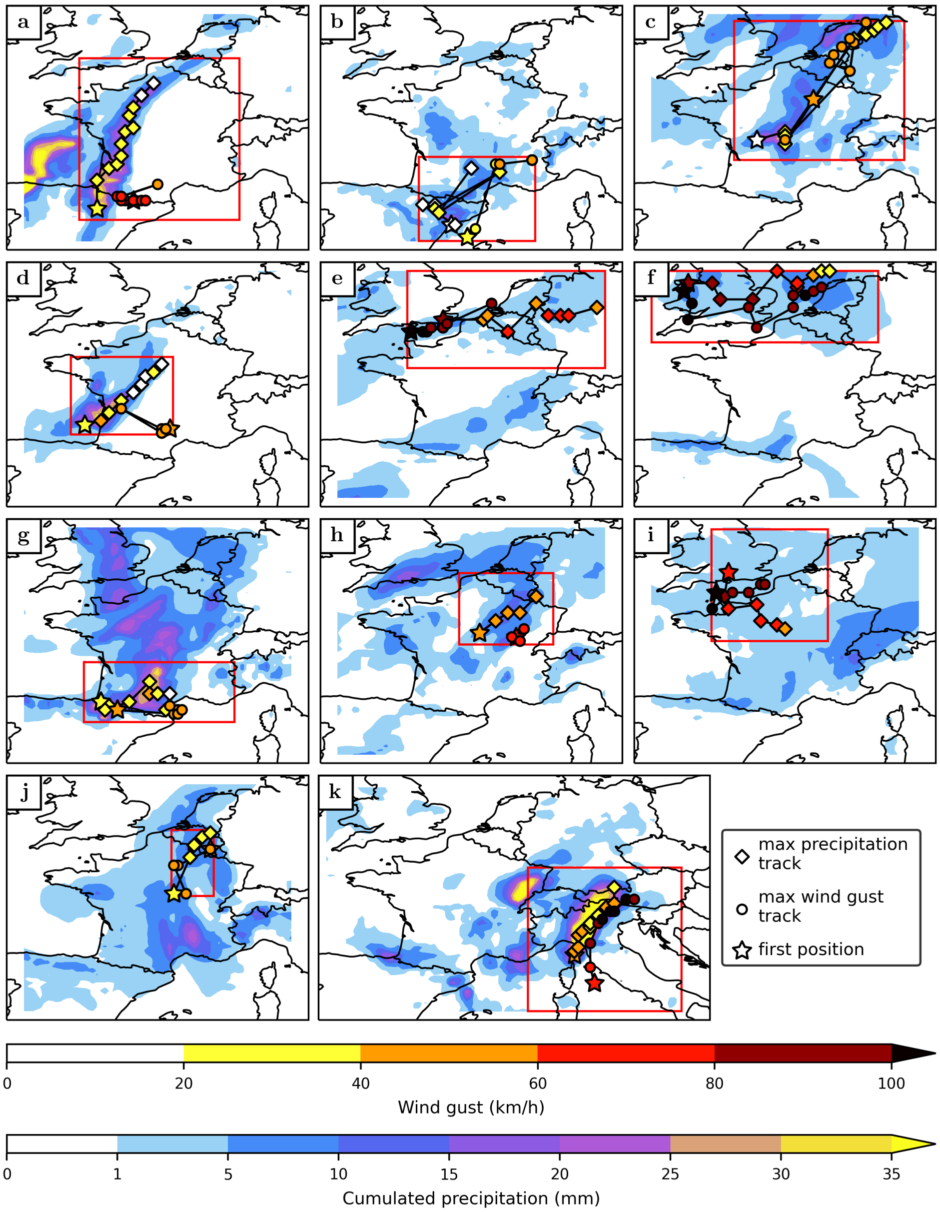

Figure 2. Tracking of derechos over France. For each event, the track of hourly maxima of wind gusts (circle markers) and precipitation (square markers) over the selected area (red rectangle) are represented from the initial tracking time (first maximum position stressed by a star marker) . The facecolor of each marker codes the corresponding value of wind gust, as shown on the top colorbar. We also represent the cumulated precipitation during the tracking time with color shadings (bottom colorbar). (a) derecho of July 25 and 26 1983. (b) derecho of August 17, 2003. (c) derecho of July 12, 2010. (d) derecho of July 26 and 27, 2013). (e) derecho of January 3, 2014. (f) derecho of January 25, 2014. (g) derecho of August 8, 2014. (h) derecho of September 16, 2015. (i) derecho of March 2, 2016 tracked between. (j) derecho of April 29, 2018. (k) derecho of August 18, 2022.

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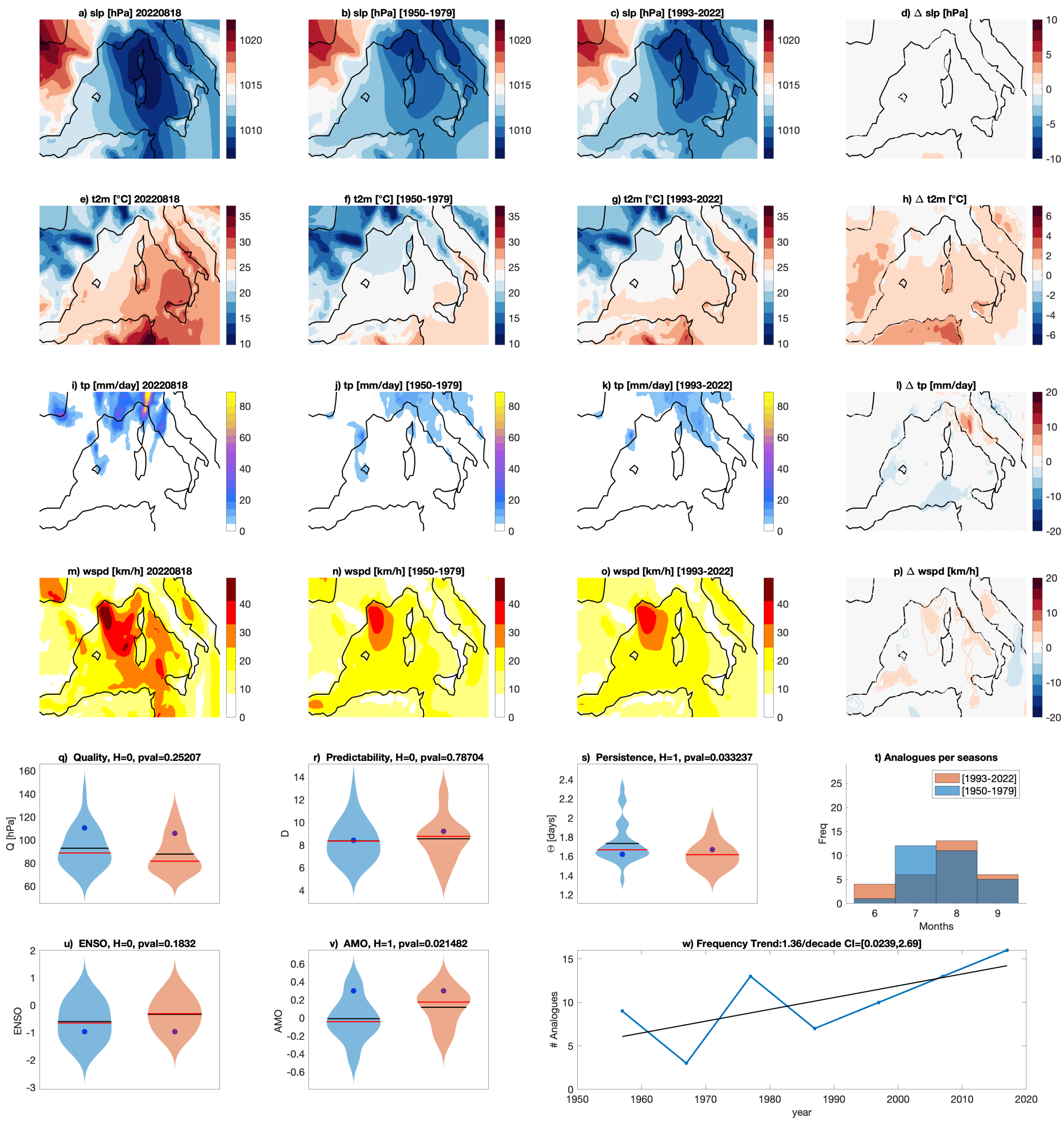

Figure 3. Attribution for the 18 August 2022 derecho storm. Daily mean sea-level pressure slp (a), 2-meter temperatures t2m (e), total precipitation tp (i), wind-speed wspd (m) on the day of the event. Average of the 29 sea-level pressure analogues found for the counterfactual [1950-1979] (b) and factual [1993-2022] (c) periods and corresponding 2-meter temperatures (f,g), daily precipitation rate (j,k) and wind speed (n,o). Δslp (d), Δt2m (h), Δtp (i) and Δwspd (p) between factual and counterfactual periods: colored-filled areas show significant anomalies with respect to the bootstrap procedure. Violin plots for counterfactual (blue) and factual (orange) periods for the analogues Quality Q (q) the Predictability index D (r), the Persistence index Θ (s) and the distribution of analogues in each month (t). Violin plots for counterfactual (blue) and factual (orange) periods for ENSO (u) and AMO (v). The number of analogues per decade (blue) and its linear trend (black) in (w). Values for the peak day of the extreme event are marked by a dot. Titles in (q–v) report the results of the Cramér-von Mises test H and the pvalue pval. Title in panel (w) includes the value of the linear trend slope and its confidence interval CI in square brackets.

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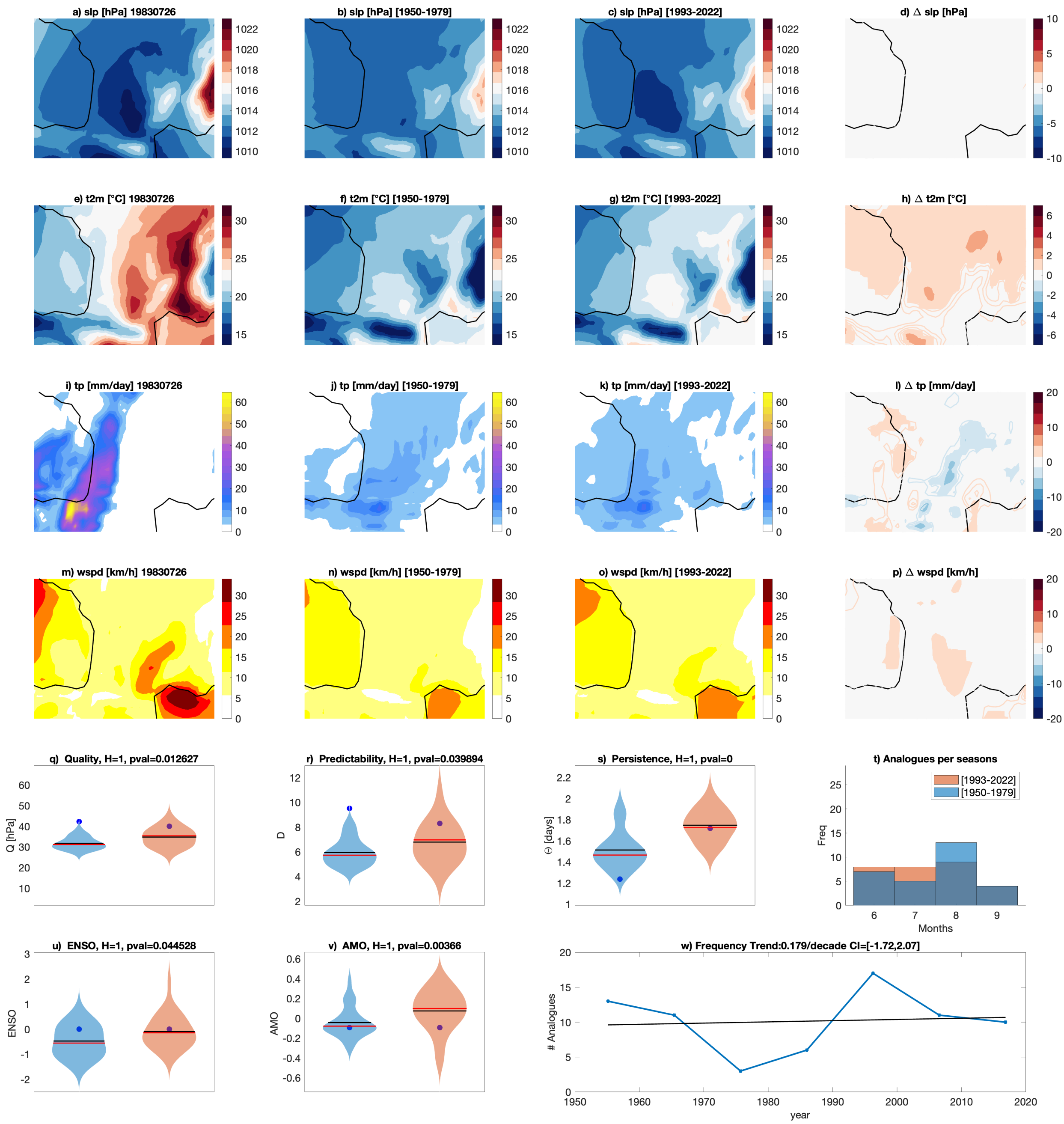

Figure A1. As in Figure 3, but for the 26 July 1983 derecho storm

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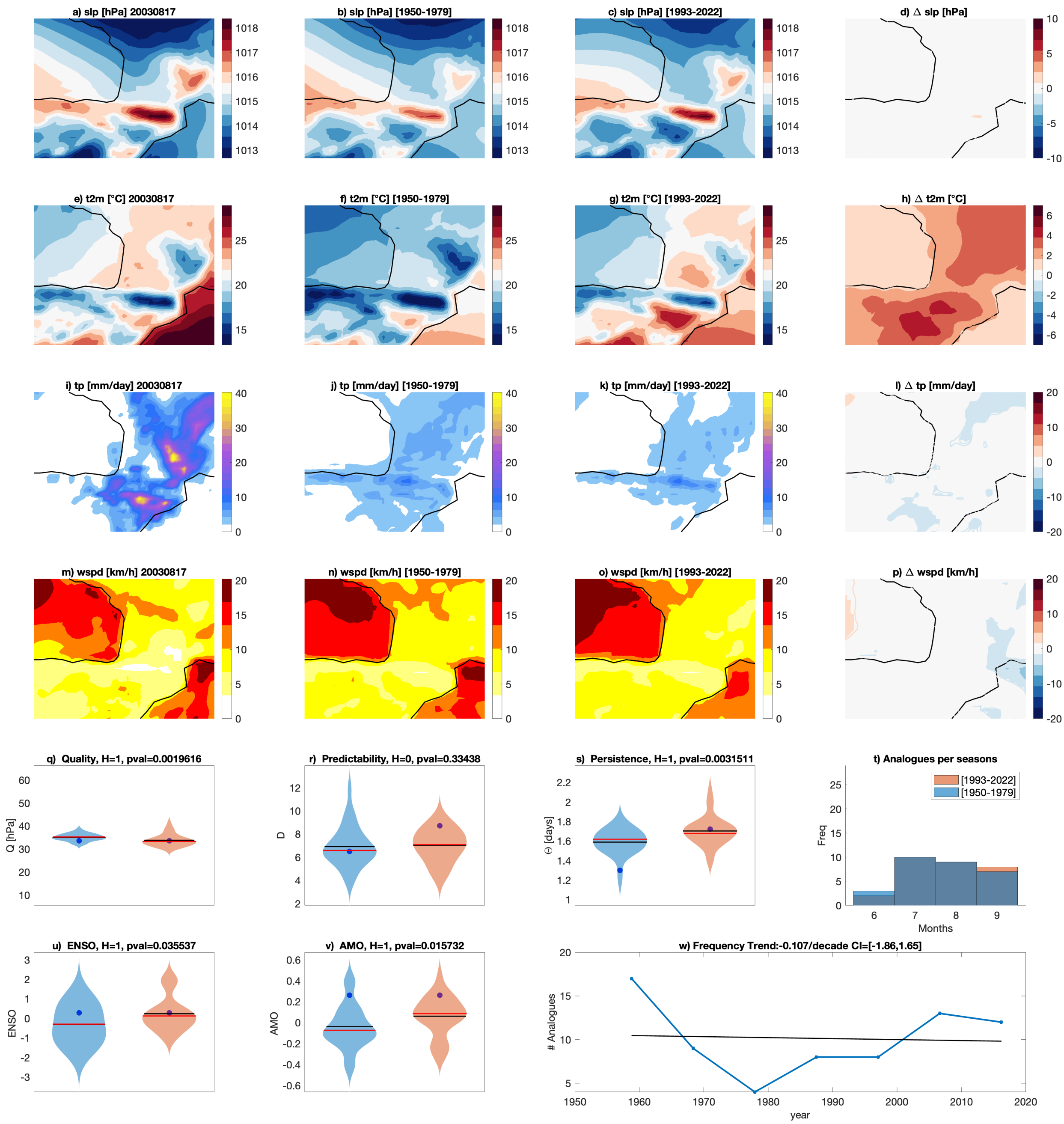

Figure A2. As in Figure 3, but for the 17August 2003 derecho storm.

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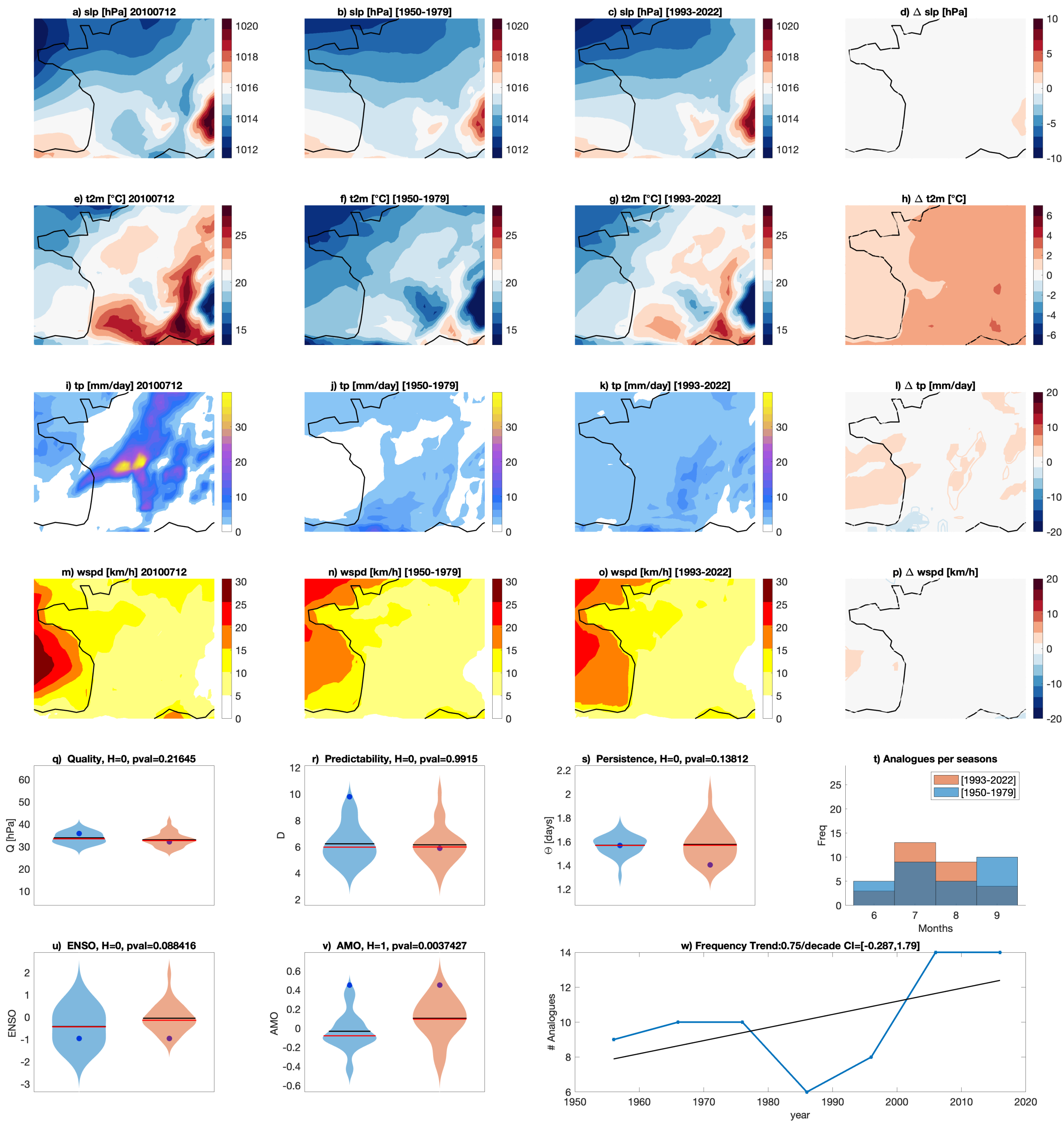

Figure A3. As in Figure 3, but for the 12 July 2010 derecho storm.

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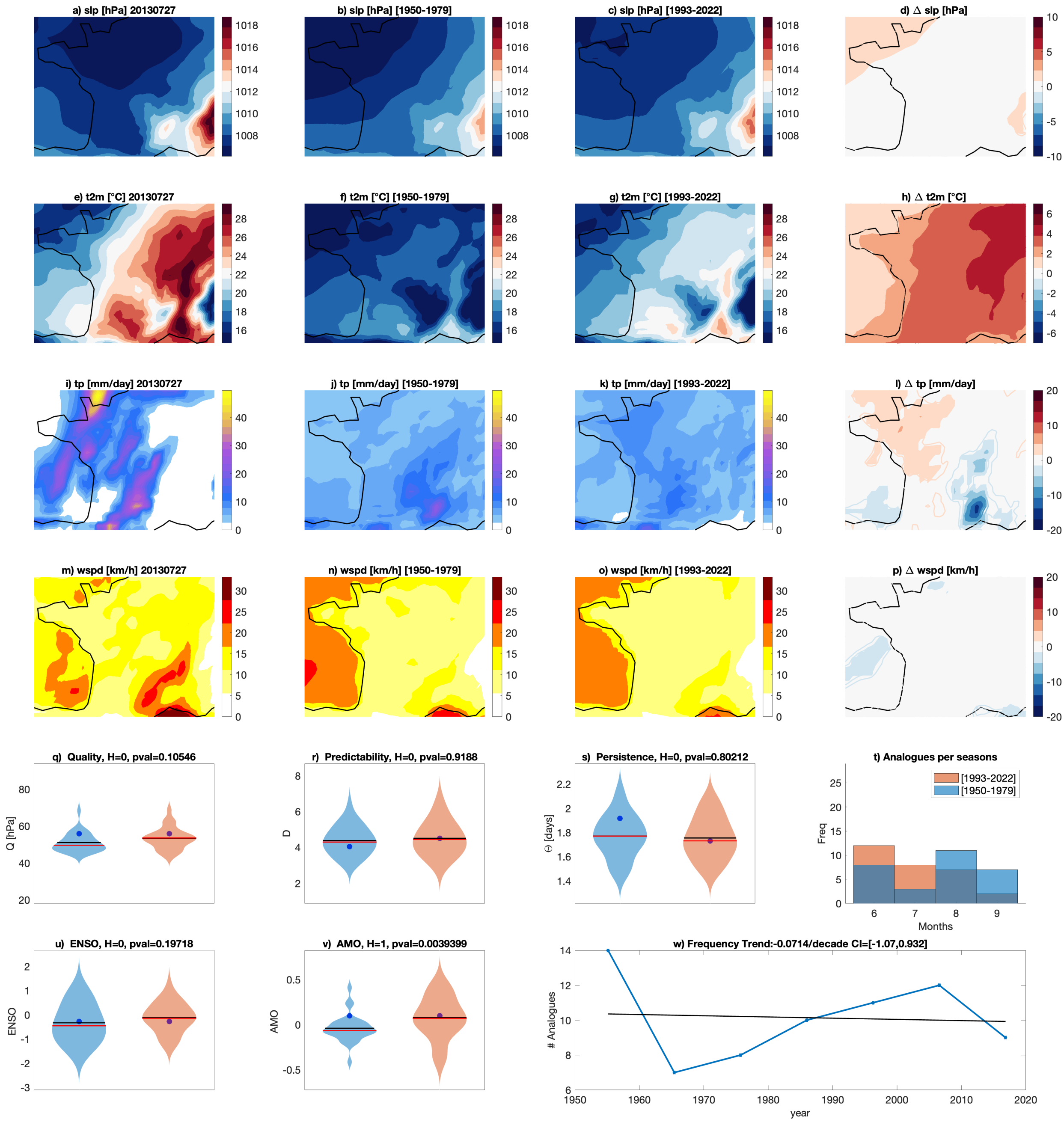

Figure A4. As in Figure 3, but for the 27 July 2013 derecho storm.

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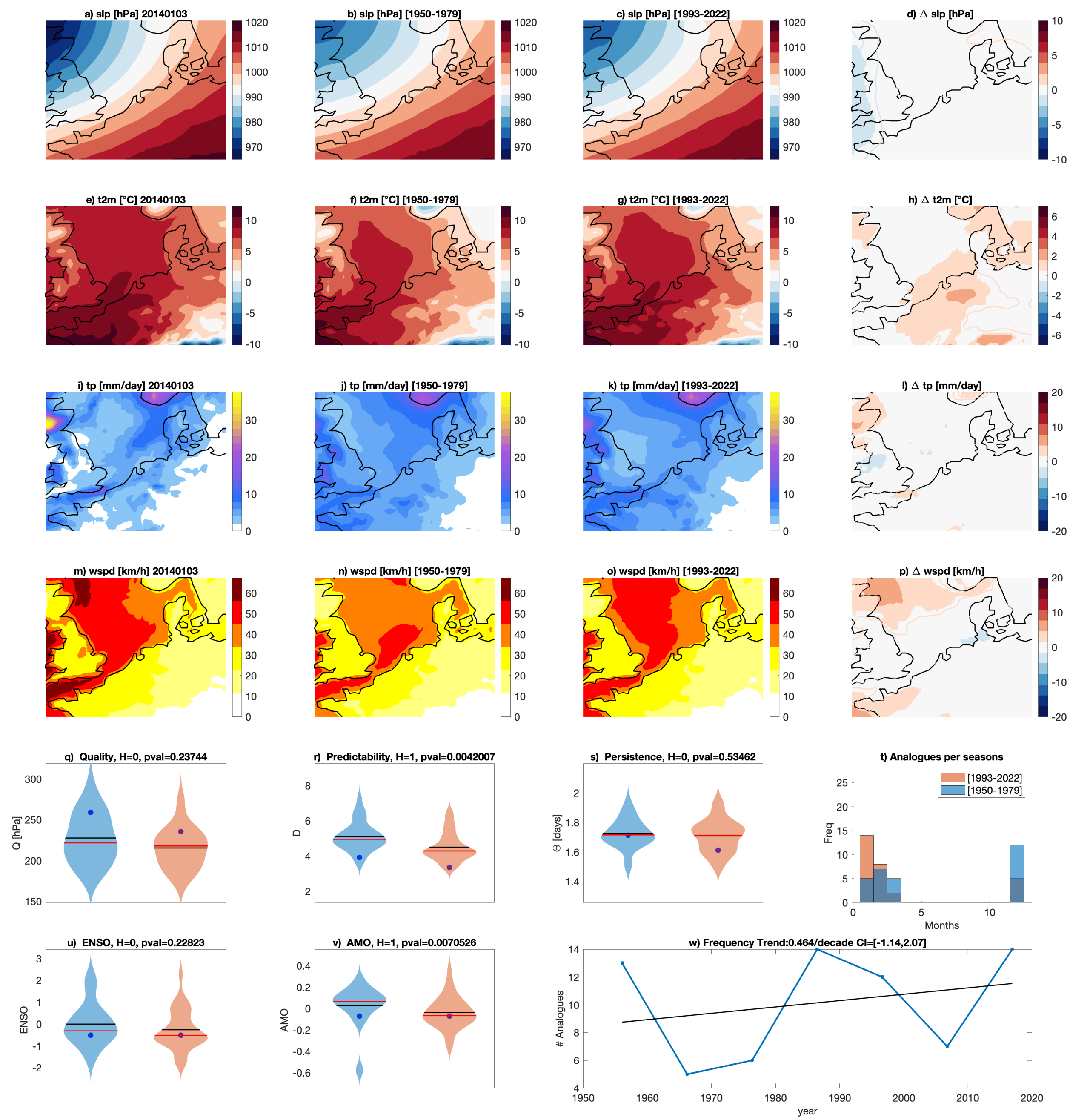

Figure A5. As in Figure 3, but for the 03 January 2014 derecho storm.

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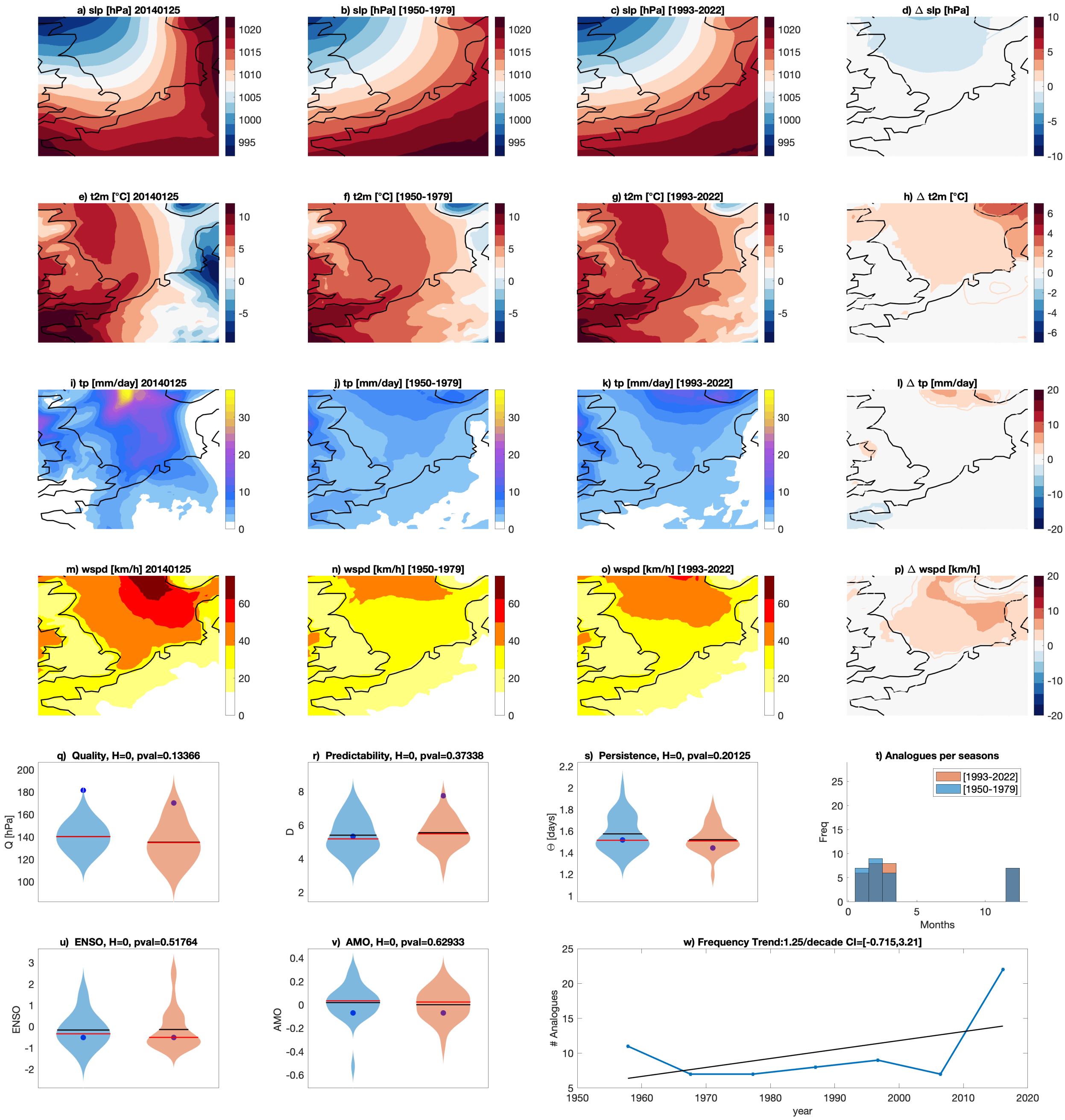

Figure A6. As in Figure 3, but for the 25 January 2014 derecho storm.

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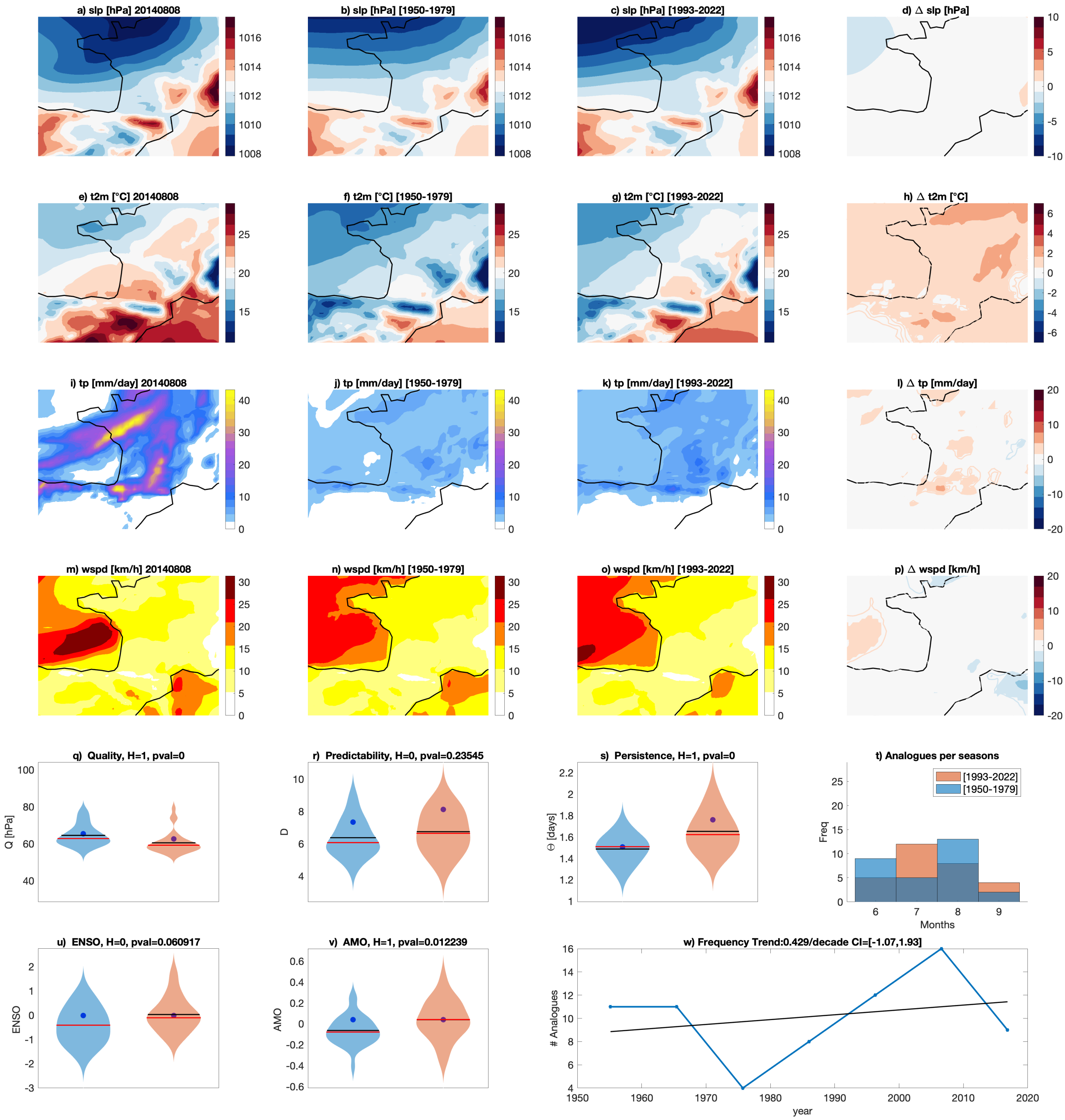

Figure A7. As in Figure 3, but for the 08 August 2014 derecho storm.

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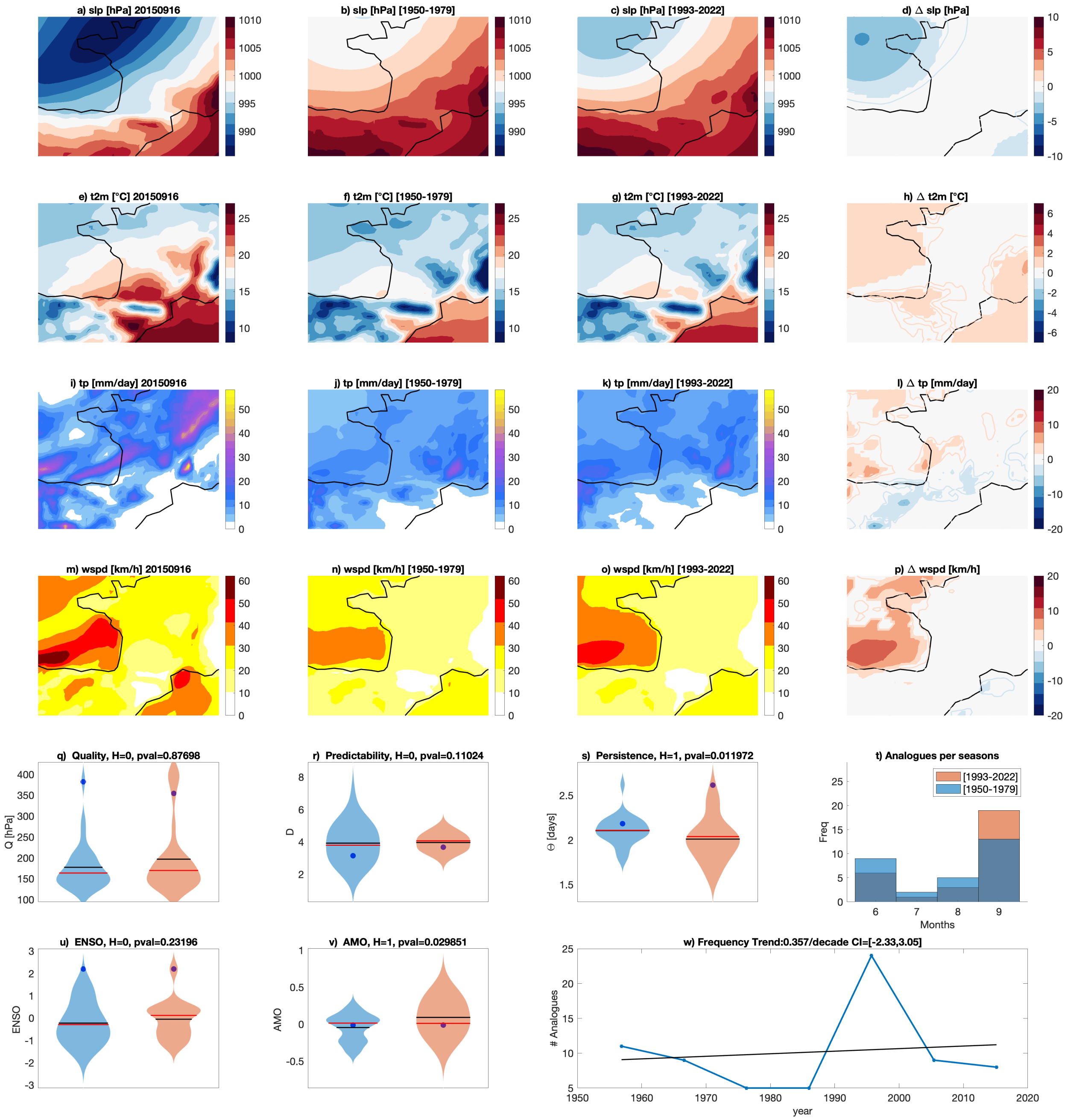

Figure A8. As in Figure 3, but for the 16 September 2015 derecho storm

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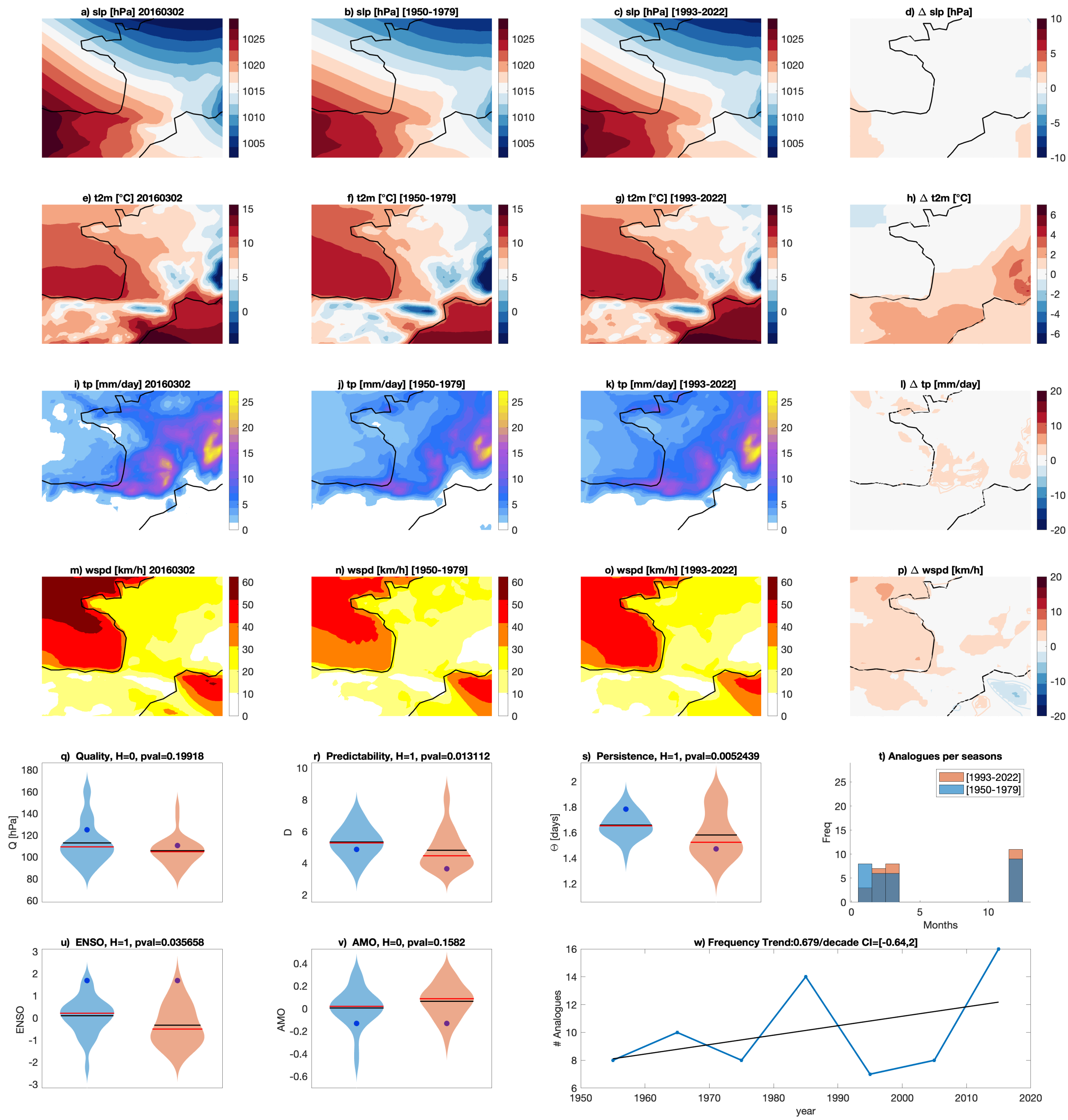

Figure A9. As in Figure 3, but for the 02 March 2016 derecho storm

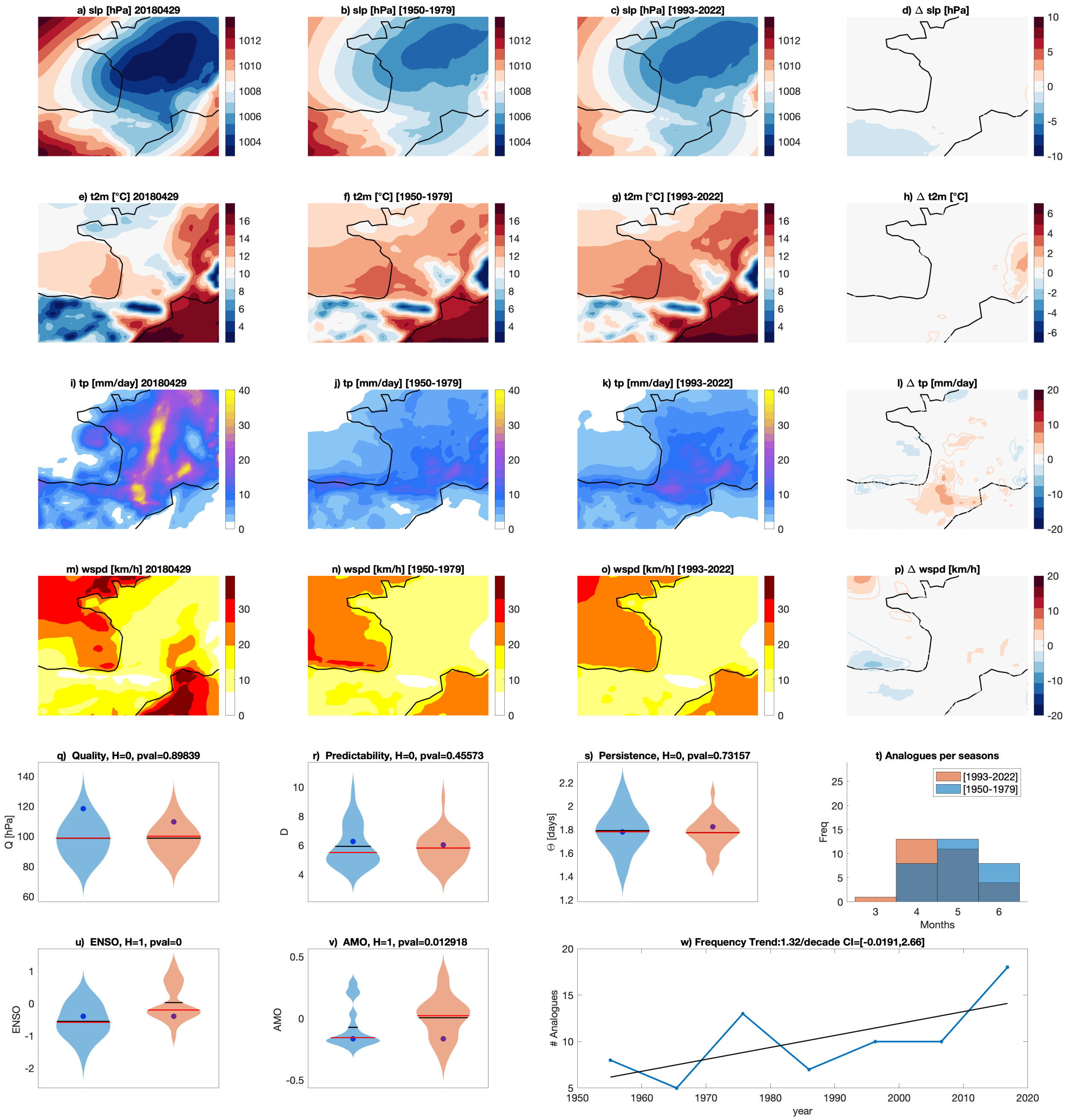

Figure A10. As in Figure 3, but for the 29 April 2018 derecho storm