Analyzing 23 years of warm-season derechos in France: a climatology and investigation of synoptic and environmental changes

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Abstract. ~~A derecho is a type of severe convective windstorm characterized by a swath of severe wind gusts several hundred of kilometers long. Such storms are known for there potential to cause widespread damage and for there threat to infrastructures and people, particularly~~

Derechos are severe convective storms known for producing widespread damaging winds. While less frequent than in the United States of America (USA)~~. Although less frequent~~, derechos also occur in Europe. ~~A recent example is the derecho of~~ The notable European event on 18 August 2022 ~~that produced damaging surface wind gusts (>~~exhibited gusts exceeding 200 ~~km/h) and affected Corsica, Italy, Slovenia, Austria and Czech Republic within~~ $\mathrm{km\,h^{-1}}$, spanning 1500 km in 12 hours. ~~In this study we create~~ This study presents a first climatology of ~~recent~~ warm-season derechos in France~~. We identified twenty-nine (29~~, identifying thirty-eight (38) events between 2000 and ~~2022 (23 years) using severe wind gust reports and satellite imagery. Derechos~~ 2022. Similar to Germany, derechos in France are ~~much less frequent and intense than in the USA, but are more similar to those in Germany. Some differences exist with more frequent events in August and a~~ associated with a southwesterly circulation and display comparable frequencies. While a suggestive trend of higher late-season frequency and a potential larger proportion of ~~short-lived low-end intensity events . In a second part, we analyse changes in synoptic conditions and environmental convective parameters associated with past warm-season derechos. To do so, we compare atmospheric circulations encoded in~~ low-intensity events in France are observed, caution is warranted due to the lack of statistical significance arising from a relatively small sample size. The study also examines synoptic and environmental changes linked with analogues of the 500 hPa geopotential height patterns associated with ~~derechos in a relative~~ past warm-season derechos, comparing analogues from a relatively distant past (~~1950-1980) , when warming was still limited, and in a recent past (1992-2022~~1950–1980) with a recent period (1992–2022). For ~~the majority of the events, we find a significant signal of increased~~ most events, a notable increase in convective available potential energy (CAPE) ~~consistent with overall trends in the Mediterranean basin while we find inconsistent changes in~~ is observed, consistent with Mediterranean trends. However, there is no consistent change in 0–6 km vertical wind shear in the recent period. These ~~changes are almost always correlated~~ environmental shifts align with higher near-surface temperatures~~and shifts in the~~ , altered mid-level atmospheric flow pat-

terns~~and often associated with increased rainfallvolume. It remains unclear to what extent those changes are attributable to~~ , and often, increased rainfall. The role of anthropogenic climate change ~~as we cannot rule out the influence of factors~~ in these changes remains uncertain, given potential influences of natural variability factors such as the ~~El-Nino~~ El Niño Southern Oscillation (ENSO) or the Atlantic Multidecadal Oscillation (AMO).

1 Introduction

~~The term "derecho" (Hinrichs, 1888) is used to describe convective storm episodes that are characterized by a particularly long-lasting and widespread production~~ During the night of August 17 to 18, 2022, a mesoscale convective system (MCS) originated over the northern Balearic Islands, initially forming as a line of thunderstorms that gradually curved into a bow echo. This system swiftly propagated to the northeast, impacting Corsica in the early morning before reaching central and northern Italy, Slovenia, Austria, and the Czech Republic within a span of 12 hours. Notably, the convective system was sustained by the exceptionally warm sea-surface temperatures (SST) of the Mediterranean Sea, leading to intense downbursts and surface wind gusts reaching up to 225 $\mathrm{km\,h^{-1}}$ in Corsica. The severity and extensive destruction caused by this extraordinary storm caught the general public by surprise. The event, resulting in 12 casualties, over 100 injuries, and disruptions to electric power lines (Wikipedia), prompted immediate inquiries into its uniqueness, comparisons with similar past events, and considerations of the potential role of anthropogenic climate change in contributing to such occurrences. In particular, the warming of the Mediterranean Sea (with anomalies larger than to +3°C recorded during the summer with respect to the seasonal values for the period 1990–2020) has been found to have significantly contributed to the development and intensity of the 18 August 2022 derecho-producing MCS (González-Alemán et al., 2023), likely by providing significant moisture and heat to the lower levels of the atmosphere, increasing convective instability.

This storm aligns with the definition of a “derecho” as described by Hinrichs (1888), a term denoting convective storm episodes marked by prolonged and widespread occurrences of damaging downbursts. More specifically, a derecho is ~~usually defined as "~~typically defined as “any family of downburst clusters ~~produced~~ generated by an extratropical mesoscale convective system~~(MCS)",following~~ ,” in accordance with Johns and Hirt (1987).

The associated radar signatures generally ~~have~~ exhibit predominantly linear characteristics, ~~with bow echoes~~ often incorporating bow echoe(s) indicative of regions with the highest wind speeds (Fujita, 1978). Derechos are ~~often subcategorized in "serial" or "progressive" type derechos (Johns and Hirt, 1987; Squitieri et al., 2023a; Corfidi et al., 2016). A "progressive"~~ commonly classified into two types: “serial” and “progressive” (Johns and Hirt, 1987; Corfidi et al., 2016; Squitieri et al., 2023a). A “progressive” derecho is characterized by a ~~fast-moving MCS with~~ rapidly propagating MCS featuring a long-lived bow echo pattern~~on radar display, almost perpendicularly oriented with respect~~ , nearly perpendicular to the mean wind direction~~and usually occurs~~ . Typically occurring in the warm season (~~May-August). This~~ May–August), this type of derecho ~~often move~~ propagates faster than the mean wind and is associated with high ~~instability. Other common features include~~ convective instability. Key features include a rear-inflow jet and mesoscale vortices. ~~The other type of derecho, "serial" derecho , typically features~~ In contrast, a “serial” derecho typically showcases an extensive squall line with a ~~line echo wave pattern~~ Line Echo Wave Pattern (LEWP)

~~oriented~~ (Nolen, 1959) embedded within a cold front. This type ~~of derecho usually~~ tends to occur in the cold season (September~~-~~–April) in an environment characterized by strong forcing and low instability. ~~Those convective systems move typically~~ Convective systems of this type generally propagate more slowly than ~~the "progressive" derechos.~~ “progressive” derechos.

~~Different~~ Various criteria have been ~~used to define a series~~ employed to delineate a sequence of downburst clusters as a derecho~~from~~, using observational data such as wind ~~gusts~~ gust reports and weather radar data. For instance, Johns and Hirt (1987) proposed the following criteria: i) a concentrated area of convective ~~wind-gusts nature~~ wind gust with a speed greater than or equal to 26 ~~m/s or – when~~ $\mathrm{m\,s^{-1}}$ or—when wind-speed measurements are not ~~available – the~~ available—the presence of damage following downbursts. The major axis length must be of at least 400 km; ii) the convective gusts must have an identifiable spatio-temporal progression, iii) at least 3 gusts greater than or equal to 33 ~~m/s~~ $\mathrm{m\,s^{-1}}$ must be measured or assessed on the basis of damage within the area covered by the episode and these reports must be separated by at least 64 km from each other; iv) there must be no ~~interruption of~~ more than 3 hours between two ~~successive severe wind gusts~~ consecutive severe wind gust reports; v) the associated convective system must have temporal and spatial continuity in surface pressure or wind field; vi) all the wind ~~gusts reports must emanates~~ gust reports must emanate from the same MCS based on radar data.

~~However, later studies have often relaxed and/or modified some of these criteria and~~ Nevertheless, subsequent studies have frequently adjusted or relaxed the criteria outlined above, particularly the most restrictive ~~one~~ criterion (iii)~~as it was argued~~. It was argued by Bentley and Mote (1998) that there is no explicit reference to wind threshold criteria in the common definition of ~~derecho~~ derechos as a family of ~~downbursts clusters Bentley and Mote (1998); Fujita and Wakimoto (1981).~~ downburst clusters by Fujita and Wakimoto (1981). Notably, Coniglio and Stensrud (2004), Bentley and Mote (1998)~~and Gatzen et al. (2020) for instance, have not retained this criterionand instead assigned an intensity to the event depending~~, and Gatzen et al. (2020) have opted not to retain this criterion. Instead, they assigned intensity to events based on the number of ~~reports of wind gusts~~ wind gust reports at different thresholds~~(moderate intensity when there at least~~. Each event is distinctly assigned to one of the intensity categories: high intensity, determined when there are a minimum of 3 reports of wind gusts ~~greater than 33 m/s, high-end intensitywhen there~~ surpassing 38 $\mathrm{m\,s^{-1}}$; moderate intensity, designated when there are at least 3 reports of wind gusts ~~greater than 38 m/s, and low-end intensity otherwise).~~ exceeding 33 $\mathrm{m\,s^{-1}}$; and low intensity for events that do not meet either of these criteria. These categories are mutually exclusive.

In 2016, Corfidi et al. (2016) proposed a more ~~restrictive definition of derecho which includes only~~ stringent definition of derechos, focusing exclusively on the most severe, long-lived ~~"progressive"~~ “progressive” or warm-season derechos~~, as the~~. This distinction arises from the different dynamics and environments associated with ~~"progressive" and "serial" derechosare very different. In particular,~~ “progressive” and “serial” derechos. Serial derechos are associated with “external” synoptic-scale forcing for ascent, while progressive derechos are characterized by more “internally driven” dynamics. The persistence of progressive derechos is attributed to the presence of mesoscale features such as a rear-inflow jet, a well-defined surface cold pool, and the swift downstream propagation of new updrafts along the gust front of the cold pool (Corfidi, 2003; Schumacher and Rasmusse . The refined definition proposed by Corfidi et al. (2016) stipulates that the damage swath “~~The damage swath~~ must be nearly continuous, at least 100 km wide along most of its extent, and 650 km long”. ~~This definition also requires some~~ Additionally, this definition requires clear evidence of radar features~~such as~~, including bow echoes, mesoscale vortices, and rear-inflow jets.

For a ~~review~~ comprehensive overview of research on derechos~~including the different set of~~, including the varied criteria used in ~~the~~ past studies, ~~see e.g. Squitieri et al. (2023a)~~refer to recent the reviews by Squitieri et al. (2023a, b).

~~The derechos are phenomena that are mainly documented in the United States of America, and~~ Derechos are primarily documented phenomena in the USA, particularly in the Midwest and Southern Plains, as noted by various studies (Hinrichs, 1888; Johns and Hirt, 1985, 1987; Bentley and Mote, 1998; Evans and Doswell, 2001; Coniglio and Stensrud, 2004; Ashley and Mote, 2005; Guastini and Bosart, 2016). In ~~comparison, the science of derechos~~ contrast, the scientific exploration of derechos in Europe is more recent~~in Europe, as events have only started to be~~, with events being officially recognized and reported as such since the 2000s ~~(López, 2007; Gatzen, 2004; Punkka et al., 2006; Púčik et al., 2011; Hamid, 2012; Celiński-Mysław and Matuszko, 2~~ ~~and few national climatologies have been established (Gatzen et al., 2020; Celiński-Mysław et al., 2020). In particular, there is not to our knowledge any previous work studying the climatology of~~ (López, 2007; Gatzen, 2004; Punkka et al., 2006; Púčik et al., 2011; H . Despite this, comprehensive national climatologies are scarce in Europe (Gatzen et al., 2020; Celiński-Mysław et al., 2020), and research on derechos in France ~~although several~~ is notably limited. While individual cases have been reported in scientific articles ~~(López, 2007; Gatzen et al., 2020; Hamid, 2012), or weather reports such as those~~ (López, 2007; Hamid, 2012; Gatzen et al., 2020) and in weather reports from Keraunos, the French observatory of severe convective storms (website: https://www.keraunos.org/)~~. For these reasons, the public opinion was astonished at the violence and the widespread destruction of the derecho that affected Corsica in summer 2022. This MCS formed during the night of August 17 to 18 over the northern Balearic Islands as an initial line of thunderstorms gradually curved to become a bow echo and moved rapidly to the northeast, affecting Corsica in the early morning. The system then affected central and northern Italy, Slovenia, Austria and Czech Republic, within 12 hours. The storm occurred in synoptic conditions featuring a meridional circulation with the presence of a cut-off low located between Portugal and France, a pattern associated with the so-called Spanish plume (Morris, 1986; Holley et al., 2014) and an anticyclone over the Mediterranean basin. Such a cut-off low typically produces heatwave or stormy conditions over France when positioned respectively over the Eastern Atlantic or Portugal or over Spain. In particular, the convective system was maintained by the particularly warm sea-surface temperatures (SST) of the Mediterranean sea and convection produced intense downbursts with up to 225 km/h surface wind gusts recorded over Corsica. With 12 casualties, over 100 people injured and disruption of electric power lines (Wikipedia), there was immediate questioning about whether this exceptional storm was unique or other similar events have occurred in the past, and whether climate change had played a role in favoring this event. While the 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) has very likely promoted the development of 2022 European derecho, an assessment of the role of human-induced climate-change on the occurrence of the~~, there is currently no previous systematic study of derecho climatology in the country. Recognizing this gap in research motivates our current study, where we aim to provide a first analysis of derecho occurrences in France and contribute to the broader understanding of these phenomena in the European context.

Unraveling the nuanced impact of anthropogenic climate change on severe convective events ~~is a difficult task~~poses another formidable challenge (National Academies of Sciences, Engineering and Medicine, 2016), particularly when ~~interested in convective~~ it involves discerning trends in convective hazards like convective winds (Kunkel et al., 2013). Because of their ~~scarcity and the~~

~~computational cost of simulating mesoscale convective events in global and regional climate models , it is~~ complexity involving a large range of time and spatial scales and various physical phenomena such as wind gust, precipitation and lightning, MCS are not well resolved in global climate models while they can be better simulated in convection-permitting, regional climate models although at a high computational cost (Meredith et al., 2015; Gensini and Mote, 2015; Gensini et al., 2023; Coppola et al., 2020; Ban et al. . It is therefore difficult to find clear climate change statements about severe convective storms, including derechos. Due to these modelling difficulties, even the IPCC reports do not contain ~~much~~ many strong statements about the influence of anthropogenic climate change on severe convective events. Indeed, in the AR6 report ~~(Masson-Delmotte et al., 2021), we~~ (Intergovernmental Panel On Climate Change (IPCC), 2023), the authors 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 conditions conducive to severe convection will tend to increase in the future climate~~"~~”.

~~Some studies have investigated the existence of changes in MCS~~ Numerous studies have delved into exploring potential changes in the frequency and intensity ~~(Schumacher and Rasmussen, 2020)~~of MCS (Schumacher and Rasmussen, 2020). Additionally, investigations into environmental factors influencing convection, ~~environmental predictors for convection~~such as CAPE and vertical wind shear ~~(Taszarek et al., 2021b, a; Púčik et al., 2017)~~ (Púčik et al., 2017; Taszarek et al., 2021a, b; Glazer et al., 2021) , or convective hazards~~(Battaglioli et al., 2023) with~~ (Battaglioli et al., 2023; Gensini and Mote, 2015; Gensini et al., 2023; Pichelli et al., 2 , have been conducted in the context of global warming. ~~Generally, the results show important regional discrepancies. There is however general agreement that~~ Although the findings exhibit significant regional variations, there is a broad consensus indicating an increase in rainfall rate and volume associated with MCS ~~tends to increase with global warming . For midlatitudesand Europe, CAPE has been shown to increase and 0-6~~ under global warming conditions (Schumacher and Rasmussen, 2020). Within the northern midlatitudes, studies indicate a rise in CAPE over southern Europe and the northern Great Plains of the USA, accompanied by a marginal decrease in 0–6 km wind shear ~~has been shown to slightly decrease (Taszarek et al., 2021b)~~ over southern Europe and a slight increase in the Great Plains (Taszarek et al., 2021a, b). However, ~~convective inhibition~~ these regions also witness an increase in Convective Inhibition (CIN) ~~also tends to increase, and relative humidity tends to decrease which makes difficult any statement~~ and a decline in relative humidity (Taszarek et al., 2021a; Pilguj et al., 2022), leading to an overall reduction in the fraction of conducive environments for storm initiation. This complex interplay makes definitive statements about the frequency of severe thunderstorms ~~as pointed out by Taszarek et al. (2021a); **?**. The lack of clear results about the~~ challenging, as highlighted by previous research (Kunkel et al., 2013; Taszarek et al., 2021a; Pilguj et al., 2022). The absence of unequivocal conclusions regarding the intensity and frequency of severe convective storms~~under anthropogenic climate change~~, including derechos, ~~also~~ under anthropogenic climate change motivates the analysis presented in this study.

~~The first purpose of this paper is to establish a first climatology of recent~~ This paper aims to create an initial climatology of warm-season derechos in France~~and analyse their features .~~, analyzing their characteristics in comparison with other countries ~~.~~ ~~The second~~ as its primary objective. The secondary goal is to ~~identify potential changes~~ detect potential alterations in synoptic conditions and environmental convective parameters~~such as convective available potential energy (CAPE) and bulk wind~~

shearassociated with past , including CAPE and vertical wind shear, linked to past warm-season derecho-producing MCS in the warm-season in Franceand assess the role France. The study also seeks to evaluate the contributions of climate change and natural variability in accounting for these to these observed changes.

We present in In Section 2, we delve into the methodological aspects of this our work and introduce the datasets we use: in 2.1, we present employed. Specifically, 2.1 outlines the methodology and observational datasets used to detect past derechos for detecting past derecho events over Franceand its limitations; in 2.2, we introduce the attribution methodology based on analogues of synoptic patterns, the reanalysis or observational datasetsused and we introduce the relevant assessment metrics. The results are presented in , along with associated limitations. Additionally, 2.2 introduces the methodology for detecting and attributing changes in synoptic conditions, accompanied by the presentation of the reanalysis and observational datasets. Moving on to Section 3for: , we present the outcomes related to the detected derechosand the analysis of , their frequency, intensity, and geographical distribution in comparison with established climatologies in Germany or the Unites States of America (USA) USA (3.1); the . Furthermore, we discuss the detailed attribution for the case of the 18 August 2022 derecho in detail (3.2); the Section 3.2 and provide an overall attribution for all events , with their interpretation (3.3)with interpretations in Section 3.3. Finally, we conclude draw conclusions on the results and limitations of this study and we discuss the perspectives for future work engage in a discussion on future perspectives in Section 4.

2 Data and Methods

2.1 Derechos Derecho detection

Similarly to Gatzen et al. (2020) who established a climatology of derechos over Germany between Following the methodology employed by Gatzen et al. (2020) in establishing a derecho climatology for Germany from 1997 and to 2014, we use utilize daily weather station data from Météo-France (automatic stations of type 0 and 1)to do a first selection of the . Our initial step involves selecting warm-season days (May, June, July, August) with at least , September) where more than 5 stations reporting report a severe daily wind gusts (measured wind speed greater than gust, defined as a measured wind gust speed exceeding 25 m/s). We then filter out the days when no $\mathrm{m\,s^{-1}}$. Following this, we eliminate days without a concentrated area of wind gusts reports is found i. e. when the reports are spread out across the map meaning there are likely not generated by a single MCS . In case they are missing because of an unsufficient number of reportsgust reports by applying the criterion that the area must cover at least 400 km along its major axis. Additionally, we stipulate that wind gust reports should be within 200 km of each other, and that there should be no more than a 3-hour interval between successive reports, aligning with the methodology employed by (Coniglio and Stensrud, 2004). To circumvent the limited geographical coverage of wind reports to France, we use severe wind gust reports from three additional sources: (i) the Integrated Surface Database (ISD) (Smith et al., 2011) from the National Oceanic and Atmospheric Administration (NOAA) (accessible from https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database), composed of worldwide surface weather observations including synoptic observations; (ii) German Weather Service (DWD) weather station data, accessible at https://cdc.dwd.de/portal) and (iii) the European Severe Weather Database (ESWD) (accessible at https://eswd.eu/) created by the European Severe Storm Laboratory

(ESSL) (Dotzek et al., 2009) whenever the associated MCS track extends into other countries. The ESWD provides detailed and quality-controlled reports from severe convective events in Europe including severe wind gusts, heavy rain, hail, tornadoes, and damaging lightning from a variety of sources. For our study, we only retained reports at minimum level quality QC1 (“report confirmed by reliable source”). These reports originate from various channels, including weather stations providing specific wind gust speeds and wind gust damage reports, such as those involving fallen trees. However, the latter type of report lacks precise wind gust speed information, impeding the accurate estimation of derecho intensity. In cases where reports are insufficient, we also ~~includes days for which a derecho has~~ consider days on which derechos have been reported over France by (Gatzen et al., 2020).

Then we use the Python FLEXible object TRacKeR (PyFLEXTRKR) algorithm developed by Feng et al. (2023a) to systematically detect and track potential associated MCS for each previously selected day. This algorithm has notably been used to build a global MCS database Feng et al. (2021) using satellite imagery data, namely brightness temperature and precipitation. It has also been used to track MCS in convection-permitting simulations Feng et al. (2023b) or convective cells from radar data Feng et al. (2022). ~~For the detection and tracking of~~ To detect and track MCS, the algorithm uses brightness temperature thresholds to identify cold cloud systems (~~$T_b < 241\,\mathrm{K}$~~$\mathrm{T_b} < 241\,\mathrm{K}$) with an additional size constraint of an area ~~$> 4 \times 10^4\,\mathrm{km}^2$~~greater than $4 \times 10^4\,\mathrm{km}^2$. Precipitation data is used in addition to enable a more robust identification of MCS by requiring that an intense precipitation feature (criteria includes rain rate ~~$> 3\,\mathrm{mm/h}$~~ greater than 3 $\mathrm{mm\,h^{-1}}$ and major axis length ~~$> 100\,\mathrm{km}$~~greater than 100 km) is embedded within the cold cloud system. These criteria must be met for at least 4 hours to define a cold cloud system as an MCS. We specifically use the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals (IMERG) V06 precipitation database (Huffman et al., 2019) and the NOAA NCEP/CPC Global Merged IR (MERGIR) brightness temperature (~~T_b~~$\mathrm{T_b}$) database (Janowiak et al., 2017), as in Feng et al. (2021). Both datasets are available from the year 2000 and cover the area between 60°S and 60°N at a time resolution of 30 minutes. The MERGIR database has a finer resolution (4km) than IMERG (10 km/0.1°), so we regridded ~~T_b~~ $\mathrm{T_b}$ data to a resolution of 0.1° using xESMF python package (Zhuang et al., 2023) prior to applying the tracking algorithm. If PyFLEXTRKR detects an MCS for a specific selected date, we conduct a visual comparison, aligning the detected MCS structure, as illustrated on brightness temperature and precipitation rate maps, with the severe wind gust reports in both time and space. For illustration, a snapshot of $\mathrm{T_b}$ and precipitation rate, highlighting the contour of the detected MCS using PyFLEXTRKR, is provided in the supplementary material (Figure S1). Subsequently, we retain only those days where the reports exhibit a discernible match with an MCS along a minimum distance of 400 km.

~~Contrary to~~ In contrast to the methodologies employed by Coniglio and Stensrud (2004) and Gatzen et al. (2020)~~who used radar data to identify the convective system , we decided to use satellite data which are more easily accessible~~ , who utilized radar data for convective system identification, we opted for satellite data due to its greater accessibility (from e.g. https://disc.gsfc.nasa.gov/)~~and have a global coverage. Indeed, radar dataare often acquired,~~ , and its large spatial coverage. Radar data, commonly managed and hosted by national weather services~~and consequently cover only~~ , typically restrict coverage to national geographical domains~~. Moreover, these data are often not easily and freely accessible. As we focus on warm-season derechos, the use of radar data is less critical than for cold-season derechos whose downbursts are difficult~~

to disentangle from the associated synoptic-scale winds (Gatzen et al., 2020), and Coniglio and Stensrud (2004) found that the associated MCS were identified quite well without radar data. Nevertheless, radar , and their accessibility is often limited. Radar data would be necessary to check the existence of a well-organized mesoscale convective system crucial for studying the specific shape of MCS (e.g.with , detecting bow echoes), to make sure the wind gusts emanates ensuring wind gusts originate from the same convective systemand to match precisely , and precisely aligning the timestamps of wind gusts reports and the position of the convective system. Thusgust reports with radar echo positions. Consequently, our methodology have some limitations as we could define as a derecho may not effectively distinguish between a swath of wind gusts emanating from a produced by a well-organized bow echo and a more disorganized convective clusterthat doesn't feature a well organized structure on radar display or from one or several supercells, although . Given our focus on warm-season derechos, the use of radar data becomes less critical compared to cold-season derechos, where distinguishing damaging winds related to downbursts from associated synoptic-scale winds is challenging (van den Broeke et al., 2005; Gatzen et al., 2020). Coniglio and Stensrud (2004) demonstrated that the MCS associated with warm-season derechos can be identified quite well even without radar data. Notably, as there has been some debate about regarding whether the specific structure of the convective system that produces the producing a swath of severe wind gusts should or not be taken into account to define be considered in defining a derecho-producing MCS (Coniglio and Stensrud, 2004; Bentley et al., 2000).

The MCS detected using PyFLEXTRLR are then matched in time and space to the severe wind gusts reports from Météo-France weather stations and only the days when reports can be matched with an MCS along a distance of at least 400 km are retained. To circumvent the limited geographical coverage of wind reports to France, we use severe wind gusts reports from the European Severe Weather Database (ESWD) database (accessible at) created by the European Severe Storm Laboratory (ESSL) (Dotzek et al., 2009) whenever the associated MCS track extends in other countries. This database provides detailed and quality-controlled reports from severe convective events in Europe including severe wind gusts, heavy rain, hail, tornadoes, and damaging lightnings from a variety of sources. For our study, we only retained reports at level quality QC1 ("report confirmed by reliable source"). The reports can come from weather stations, in which case the wind gust speed is given, or by reports from wind gust damage report such as fallen trees, which doesn't allow a precise estimation of the wind gust speed and this is also a limitation, notably for the estimation of the derecho intensity(Bentley and Mote, 1998; Johns and Evans, 2000; Bentley et al., 2 , we assert that our approach is reasonable for establishing an initial climatology of these severe convective windstorms in France.

2.2 Detection of changes in synoptic patterns

To understand how anthropogenic climate change may have influenced the synoptic patterns related to associated with severe convective events like derechos, we consider analogues of patterns of atmospheric circulation. Although there is no While a direct one-to-one correspondence between large scale synoptic patterns and the occurrence of derechos, the former are typical recurrent large scale conditions that are associated with favorable environment for derecho occurrences may not exist, these patterns commonly represent recurring large-scale conditions conducive to the development of severe convective events(Bentley et al., 2000; van Delden, 2001; Coniglio et al., 2004; Lewis and Gray, 2010; Markowski and Richardson, 2010; Yang et al.

. To investigate this, we are examining changes in temperature, precipitation, wind speed, along with proxies or environmental parameters that are commonly used as predictors for convection, namely convective available potential energy (CAPE) and 0-6 km wind shear (named hereafter deep layer shear or DLS) (Taszarek et al., 2020b, 2019) by identifying similarities between large-scale geopotential height fields at (Bentley et al., 2000; van Delden, 2001; Coniglio et al., 2004; Lewis and Gray, 2010; Markowski a . We use the geopotential height field at 500 hPa associated with historical derechos in the past (1950-1980) and the recent past (1992-2022hPa (Z500) as a proxy of large-scale atmospheric flow, in a similar way as Burke and Schultz (2004), Coniglio et al. (2004) and Gatzen et al. (2020) To isolate the impact of atmospheric circulation determined by Z500 gradients, we eliminate the geopotential height offset, which exhibits a trend associated with anthropogenic climate change (Christidis and Stott, 2015). This is achieved by subtracting the mean value of each Z500 field, effectively removing the mean thermodynamic contribution of global warming. This approach allows us to concentrate on dynamical changes in the Z500 gradient directly linked to mid-level atmospheric flow. These Z500 analogues capture large-scale dynamics governing environmental conditions that drive various extreme events, including heat waves, cold waves, MCS, medicanes, extratropical cyclones, and, in our case, derecho-producing MCS. However, it is worth noting that sub-synoptic scale environments also play a key role in convective storm development, especially concerning convective initiation and the release of CAPE (Markowski and Richardson, 2010).

More specifically, for each event, we look for Z500 analogues in both a relative distant past period (1950–1980) and a more recent past period (1992–2022). Our assumption in dividing the historical past in two periods is that the past most distant period serves as a hypothetical world where the Earth's climate was only marginally affected by human activityweakly affected by greehouse gas emissions, and that 30 31 years is a sufficient period to account for natural variability in atmospheric motions. However, we must also consider This time period is also recommended by the WMO for the computation of climate normals (Arguez and Vose, 2011). Nevertheless, it is crucial to account for long-term natural variabilitysuch as that caused by , as induced by phenomena like the Atlantic Multidecadal Oscillation (AMO) or the El Niño-Southern Oscillation (ENSO). If a direct influence of we can exclude a direct impact from such low-frequency variability is excluded, then changes in by examining the indices related to these phenomena alongside the analogues between the two periods we consider under investigation, any changes in the analogues can be attributed to the climate change signal. The method ensures that comparisons are relevant, unlike purely statistical modeling techniques, which aim to analyze signal of climate change. While conventional statistical techniques, rooted in extreme value theory, focus on analyzing univariate 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.

We specifically compare the 1992-2022 geopotential height patterns at 500 hPa (Z500) fields to fields from 1950-1980, when warming was much more limited. To account only for the atmospheric circulation which is determined by Z500 gradients we remove the offset of geopotential height which has a trend linked with anthopogenic climate change Christidis and Stott (2015) . To do so, we substract the mean value of each Z500 field to remove the mean thermodynamic contribution of global warming and focus on dynamical changes in the Z500 gradient which is directly linked to the quasi-geostrophic flow. These Z500 analogues reflect the mid-level large-scale dynamics that controls environmental conditions which can drive extreme events

~~such as heat waves, cold waves, MCS outbreak, medicanes, tropical and extratropical cyclones and, in the present case, MCS associated with derechos. Nevertheless, one should keep in mind that sub-synoptic scale environments such as fronts also play a key role in~~ underlying atmospheric processes, our approach ensures that comparisons of variable maps are conditioned on the associated atmospheric circulation. Additionally, the ~~development of convective storms, particularly when it comes to convective initiation and the release of latent CAPE (Markowski and Richardson, 2010).~~

~~The attribution protocol~~ method enables the identification of unprecedented weather events resulting from previously unobserved atmospheric circulations, posing a statistical challenge in attributing the event's likelihood to climate change. The attribution methodology 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 to the synoptic patterns associated with ~~historical~~ severe convective events, and more specifically to derechos.

~~We use daily averaged Z500,~~ In our examination, we analyze changes in temperature, precipitation, and wind speed, ~~2-meters temperature, and consider daily cumulative precipitation, daily maximum~~ along with proxies and environmental parameters commonly utilized as predictors for convection associated with these analogues within the historical period. Specifically, we focus on the most unstable Convective Available Potential Energy (CAPE) and 0–6 km vertical wind shear, calculated as the wind vector difference between 500 hPa and 10 m, referred to as deep-layer shear (DLS). CAPE serves as a proxy for buoyant instability, intricately linked to the intensity of convective updrafts (Holton and Hakim, 2013), while vertical wind shear fosters the organization of convection (Markowski and Richardson, 2010; Schumacher and Rasmussen, 2020). Numerous studies have demonstrated an augmented probability of severe convection with increasing levels of instability and vertical wind shear, frequently employing CAPE and DLS ~~computed from ERA5 (Hersbach et al., 2018) hourly fields.~~ as metrics (Brooks et al., 2003; Trapp et . We use data from ERA5~~is~~ (Hersbach et al., 2020), 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°. ~~Our choice of using~~ We opted for ERA5 data ~~for this study is firstly motivated by the consistency of the datasetthrough a long period of time~~ in this study primarily due to the dataset's remarkable consistency over an extensive time span (73 years)~~which enables the possibility of detecting changes in the large dynamics. Moreover, the~~ , facilitating the detection of changes in large-scale dynamics. The global nature of ~~this datasets allows to avoid the problems of mixing data-sets from different~~ ERA5 also mitigates issues related to combining datasets from diverse national weather services~~and ensures~~ , ensuring a uniform spatial and temporal coverage. ~~However, there are some caveats due to~~ Nevertheless, it's important to acknowledge certain caveats arising from the long-term ~~improvement of observation instrumentsincluding satellites that can affect~~ advancements in observation instruments, including satellites. These advancements may impact the uniformity of ~~the quality of the dataset and potentially induce spurious trends~~ dataset quality and have the potential to introduce spurious trends (Thorne and Vose, 2010; Hersbach et al., 2020). In addition, parameterizations can bring errors in the estimation of convective parameters such as CAPE and modeled precipitation and wind gusts (Taszarek et al., 2021c). Despite these considerations, ERA5 continues to be regarded as one of the best reanalyses currently available.

~~We also consider 2-meters~~ For each period, we examine all daily averaged Z500 maps and select the best 37 analogues, i.e. the maps minimizing the Euclidean distance to the event map itself. The number of 37 corresponds approximately to the smallest 8 ‰ 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 date of the event considered is discarded. 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 season in which each event occurs (in this case the warm season comprising May, June, July, August and September). This allows us to identify possible changes in seasonality—defined as the relative frequency of analogues occurrence per calendar month—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. We then examine composites of the analogues in each period for daily averaged 2 meter temperature and wind speed, daily cumulative precipitation, daily maximum CAPE and DLS all computed from ERA5 hourly field. For comparison, we also consider daily mean 2 meter temperature and accumulated rainfall from the E-OBS observational dataset v27.0 (Cornes et al., 2018) ~~,~~ (available from https://www.ecad.eu/download/ensembles/download.php) which interpolates measurements from land weather stations across Europe on a regular grid at 0.1° resolution. To determine significant changes between the two periods, we adopt a bootstrap procedure which consists of pooling the dates from the two periods together, randomly extracting 37 dates from this pool 1000 times, creating the corresponding difference maps and marking as significant only grid point changes above two standard deviations of the bootstrap sample.

~~We divide the datasets into two periods: 1950-1980 and 1992-2022 each consisting of 30 years of daily data. We consider the first period to represent the equivalent of a "counterfactual" world with a weaker anthropogenic influence on climate than the second period, which represents our "factual world" significantly 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), the Atlantic Multidecadal Oscillation (AMO)~~ENSO, the AMO, the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and the East Atlantic (EA) and Scandinavian (SCAND) North Atlantic patterns. Piper et al. (2019) found that convection-favoring environments are strongly influenced by teleconnection patterns such as NAO, EA and SCAND and SST in Europe. The NAO, the EA and to a lesser extent ENSO have been found to have a significant role in modulating extreme precipitation events in some regions of Europe (Nobre et al., 2017). The role of AMO has been discussed, e.g., in Zampieri et al. (2017) who found an influence on pressure, precipitation and temperature patterns. Wei et al. (2021) found an influence of PDO on northwestern Europe extreme rainfall. Similarly, Casanueva et al. (2014) found a significant role of SCAND in autumn and spring on extreme precipitation in Europe.

~~For each period, we examine all daily averaged Z500 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 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 season in which each event occurs (in this case the warm season : May, June, July and August). This allows us to identify possible changes in seasonality — defined as the relative frequency of analogues occurrence per calendar month — 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~~In practice, we examine the ~~seasonality~~ association of the analogues ~~during the relevant season and their association with~~ with the aforementioned factors of natural variability (ENSO, AMO, PDO, NAO, EA, SCAND). We perform this ~~last~~ analysis using monthly indices from NOAA/ERSSTv5 data and retrieved from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (accessible at https://climexp.knmi.nl/selectindex.cgi). In particular, the ENSO index is ~~version~~ computed in region 3.4 as defined by Huang et al. (2017), and the AMO index is calculated as described in Trenberth and Shea (2006). To assess the possible association of these different indices on circulation changes between factual and counterfactual periods, we compare the distributions of each index for the analogues of the two periods and we evaluate any ~~significance~~ significant 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 cannot be excluded (H = 1). On the other hand, if the null hypothesis of equal distributions is not rejected, the observed changes in the analogues are attributed to anthopogenic climate change. All relevant figure panels display the p-value (pval) and the H-test ~~result~~ results in the title. ~~Finally, we also compute the best 3~~

We further investigate the seasonality of analogues within the warm season by quantifying the number of analogues in each month, aiming to identify potential shifts in circulation towards earlier or later months in the season. Such shifts could carry significant thermodynamic implications; for instance, if a circulation pattern associated with substantial positive temperature anomalies in early spring becomes more prevalent later in the season when average temperatures are considerably higher. To evaluate the significance of potential changes in analogue seasonality between the two periods, we apply the same statistical test that we use to compare the distributions of indices of natural variability. Additionally, we extend our analysis by computing the best 8 ‰ analogues for ~~all the 1950-2022~~ the entire Z500 dataset ~~, without dividing~~ from 1950 to 2022 without segregating it into factual and counterfactual periods~~and~~ . Subsequently, we estimate a linear trend ~~. Note that~~ for this global quantile, recognizing that the total number of analogues in all decades ~~amounts to 71. We compute~~ for this specific quantile is 89. To evaluate the significance of these trends, we calculate 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~~ 37 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 Z500 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 Z500 maps will be (Faranda et al., 2017b; Messori et al., 2017; Hochman et al., 2019). If the dimension D of the pattern assocaited with a 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~~ provides an estimate of the number of days we are likely to ~~observe~~ encounter a map that is an analogue of the one under consideration (Moloney et al., 2019). 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 factors of natural variability**: To account for the effect of natural inter-decadal variability, we analyze the distributions of ENSO, AMO, PDO, NAO, EA and SCAND 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.~~

3 Results

3.1 Detected derechos over France between 2000 and 2022

In total, we ~~found twenty-nine (29~~identified thirty-eight (38) warm-season derechos ~~that occurred over France between~~ in France from 2000 ~~and~~ to 2022. ~~A summary of the identified derechoswith~~ Table 1 presents a summary of these derechos, including their start date and time, ~~their~~ path length, duration, intensity, and affected countries~~is presented in Table 1. Additionally, we provide a figure with wind gusts reports in France and the path determined from the first and last reports of each derecho~~

~~in supplementary material. Just like~~ . Similar to the methodology of Gatzen et al. (2020), we ~~compute for each derechoits~~ computed each derecho's path length as the distance between ~~the~~ its first and last severe wind gust reports ~~, and the~~ and its duration as the time elapsed between these two reports. ~~We also define the intensity as in Gatzen et al. (2020); Coniglio and Stensrud (2004) from the observed number of wind gusts reports above thresolds : if there~~ Intensity classification follows the criteria set by Gatzen et al. (2020) and Coniglio and Stensrud (2004), where an event is deemed high intensity if there are at least 3 reports ~~$\geq 38\,\mathrm{m\,s^{-1}}$, the event is classified as high-end, if there are~~ with wind speed $\geq 38\ \mathrm{ms^{-1}}$, moderate intensity if the last condition is not met and at least 3 reports ~~$\geq 33\,\mathrm{m\,s^{-1}}$, the event is classified as moderate and the others that do not satisfy these criteriaare classified as low-end~~show wind speed $\geq 33\ \mathrm{ms^{-1}}$, and low intensity if the event does not meet the previous criteria.

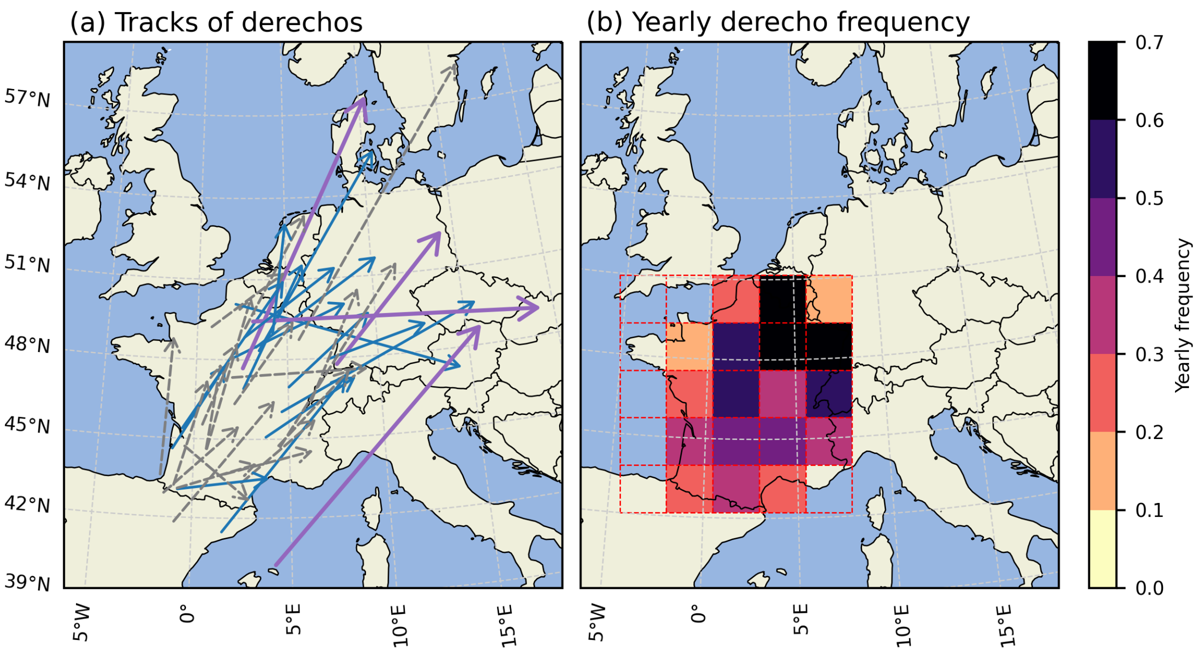

Figure 1. (a) ~~Tracks~~ Approximate tracks of warm-season derechos that affected France between 2000 and ~~2022~~ 2022. The tracks are depicted by straight arrows between the first and last severe wind gust reports. The thin broken grey lines, thin blue lines, thick purple lines respectively represent ~~low-end~~low, moderate and ~~high-end~~ high intensity derechos. (b) Heatmap of the yearly frequency of warm-season derecho computed for geographical ~~squares~~ cells of dimensions 200 km × 200 km.

~~Compared~~ In comparison to Germany, we observe a slightly ~~more frequent occurrence~~ higher frequency of warm-season derechos in France ~~(1.26 event per year vs~~overall (1.65 vs. 1.22 events per year)~~overall but France is about~~ , although it's noteworthy that France is approximately 50 % larger by area than Germany. ~~Relative to the size of Germany~~When considering the size difference, the observed frequency of warm-season derechos ~~is lower in France (0.82 event~~ in France is slightly lower (1.07 events per year). However~~there are important regional discrepancies as can be seen on Figure 1(a) where we plot the~~ , regional variations are significant, as depicted in Figure 1. The trajectories of all derechos ~~as the straight arrow~~

Table 1. List of warm-season derechos that affected France between 2000 and 2022. The countries are abbreviated with their ISO 3166-1 alpha-2 code.

Number	Start date and time (UTC)	Path length (km)	Duration (h)	Intensity	Affected countries
1	~~2000-07-02~~ 2 July 2000 13:55:00	560	7	~~moderate*~~ moderate	FR, BE, LU, DE
2	~~2001-07-06~~ 6 July 2001 16:45:00	500	6	~~moderate*~~ moderate	FR, CH, DE
3	~~2001-08-15~~ 15 August 2001 13:15:00	700	10	low	FR, BE
4	~~2003-05-19~~ 19 May 2003 12:45:00	960	8	~~low~~ moderate	FR, CH, DE, CZ
5	~~2003-06-14~~ 14 June 2003 05:17:00	1000	15	~~moderate*~~ moderate	FR, DE, ~~AT~~ AU
6	~~2003-07-15~~ 15 July 2003 17:27:00	460	7	moderate	FR
7	~~2003-08-17~~ 17 August 2003 07:30:00	900	~~12~~ 13	moderate	ES, FR, CH ~~, ES~~
8	~~2003-08-28~~ 28 August 2003 18:45:00	~~460~~ 490	5	~~low~~ moderate	FR, CH
9	~~2004-08-17~~ 17 August 2004 14:42:00	450	6	low	FR
10	~~2005-07-29~~ 29 July 2005 14:27:00	~~690~~ 740	10	~~high*~~ high	FR, CH, DE, CZ
11	~~2006-07-04~~ 4 July 2006 19:33:00	410	4	low	FR
12	~~2009-05-25 21:42~~ 17 September 2007 15:59:00	~~540~~ 420	5	low	FR
13	25 May 2009 21:42:00	990	11	moderate	FR, BE, NL, DK
~~13~~ 14	~~2010-07-12~~ 12 July 2010 04:30:00	~~1050~~ 1260	13	~~moderate*~~ high	FR, BE, LU, NL, DE, DK
~~14~~ 15	~~2010-07-14~~ 14 July 2010 12:11:00	~~580~~ 660	~~8~~ 10	~~moderate*~~ moderate	FR, BE, LU, NL, DE
~~15~~ 16	~~2011-06-22~~ 22 June 2011 13:08:00	470	5	~~moderate*~~ moderate	FR, CH, DE
~~16~~ 17	~~2012-06-07~~ 7 June 2012 11:24:00	600	7	low	FR, CH, DE
~~17~~ 18	~~2013-07-26~~ 20 June 2013 13:50:00	550	9	low	CH, FR, DE
19	26 July 2013 21:42:00	790	10	moderate	FR, BE
~~18~~ 20	~~2013-07-27~~ 27 July 2013 16:23:00	620	7	moderate	FR, BE, LU, NL, DE
~~19~~ 21	~~2014-08-08~~ 4 July 2014 13:49:00	510	7	low	FR, CH, DE
22	8 August 2014 15:53:00	430	6	moderate	FR
~~20~~ 23	~~2015-08-31 15~~31 August 2015 14:15:00	~~390~~ 470	6	~~moderate~~ low	ES, FR
~~21~~ 24	~~2018-07-04~~ 16 September 2015 11:33:00	490	5	low	FR, LU, BE
25	13 September 2016 14:57:00	630	8	low	FR
26	4 July 2018 13:49:00	400	6	low	FR
~~22~~ 27	~~2018-08-07~~ 14 July 2018 20:15:00	400	7	low	FR
28	7 August 2018 16:50:00	420	6	low	FR, BE, NL
~~23~~ 29	~~2018-08-09~~ 9 August 2018 09:46:00	1350	18	low	FR, DE, DK, SE
~~24~~ 30	~~2018-08-28~~ 12 August 2018 14:29:00	710	11	low	ES, FR
31	28 August 2018 17:21:00	510	5	low	FR
~~25~~ 32	~~2019-06-04~~ 23 September 2018 12:03:00	1220	9	high	FR, BE, LU, DE, CH, AU, C
33	4 June 2019 16:04:00	~~560~~ 570	6	low	FR, BE, NL
~~26~~ 34	~~2019-06-05~~ 5 June 2019 18:06:00	510	5	~~moderate*~~ moderate	FR, BE, NL
~~27~~ 35	~~2021-06-19~~ 16 June 2021 22:06:00	414	4	low	FR
36	19 June 2021 16:18:00	520	8	~~low~~ moderate	FR, BE, LU, DE
~~28~~ 37	~~2021-06-20~~ 20 June 2021 12:27:00	950	12	low	FR, CH, DE
~~29~~ 38	~~2022-08-18~~ 18 August 2022 01:35:00	1400	16	high	ES, FR, IT, SI, AU, CZ

~~List of warm-season derechos that affected France between 2000 and 2022. Unless stated otherwise, intensity is assessed from reports in France only. * intensity assessed using not only weather reports from Météo-France but also reports outside of France (from ESWD or German Weather Service DWD (data accessible at)) or intensity assessment by Gatzen et al. (2020)~~

~~linking~~ are illustrated as straight arrows connecting the geographical locations of the first and last reports ~~and 1(b) where we show~~ in Figure 1a. While this method provides a rough estimation of the MCS's actual path, it doesn't account for potential curvature in the track and lacks precision in time-dependent estimation of the MCS's propagation direction. Limitations in the available severe wind gust reports also constrain the accuracy of duration and path length estimations for derechos, introducing potential biases due to underreporting in certain regions. We also present the average number of warm-season derechos per year per 200 km × 200 km grid cells~~like in~~, following the approach of Gatzen et al. (2020) and Coniglio and Stensrud (2004)~~, counting the number of events for which~~. This involves counting the occurrences of associated severe wind gusts ~~are found in each cells. Indeed~~ within each cell, as illustrated in Figure 1b. Notably, the northeast of France ~~have~~ exhibits the highest frequency of events~~(culminating at 0.61~~, peaking at 0.65 derechos per year~~)~~, while Brittany (western part) ~~has no event. This highest frequency is lower than the maximum frequency observed in Germany for~~ registers no events. This peak frequency is comparable to the maximum observed in equivalent cells in Germany throughout the entire year and specifically for moderate and ~~high end events only~~ high-end events (0.72 per year)~~so the frequency might be comparable for the warm season and all events. However~~. In contrast, warm-season derechos are ~~much more frequent~~ more prevalent in the USA~~with~~, reaching up to 1.9 ~~event~~ events per year for ~~equal size grid cell (Coniglio and Stensrud, 2004)~~ equal-sized grid cells, particularly in the Southern Plains or the Midwest ~~(Guastini and Bosart, 2016). Most of the trajectories have~~ (Coniglio and Stensrud, 2004; Guastini and Bosart, 2016).

The trajectories of warm-season derechos in France predominantly follow a northeastern direction, ~~in agreement with~~ aligning with the patterns observed in German warm-season derechos. ~~Furthermore, looking at~~ Additionally, upon examining the daily averaged 500 hPa geopotential height ~~pattern (shown for each event in supplementary figures~~patterns (not shown), we ~~mainly~~ predominantly observe southwesterly flow associated with the events. This is consistent with the ~~preferred~~ favored development of extratropical MCS ahead of a trough or a cut-off low ~~Coniglio et al. (2004); Yang et al. (2017); Houze (2018); Gatzen (2004,~~ ~~. From the map of trajectories, there seems to be 3 main typical paths for derechos in France: i) one type of path originates in the southwest in Nouvelle Aquitaine region and move in anorth-northeast direction; ii)another type of path starts in the east or south and moves to~~ (van Delden, 2001; Gatzen, 2004; Coniglio et al., 2004; Gatzen, 2013; Yang et al., 2017; Houze, 2018; Piper et al., 2019; Ga . Many Z500 patterns associated with warm-season derechos in France bear resemblance to the Spanish Plume (Morris, 1986; Holley et al., , a typical configuration known for its association with severe convective weather in Northwestern Europe. Examining more precisely the map of tracks (Figure 1a), we note a significant number of derechos that propagate from the southern and eastern regions of France, advancing towards the east-northeast~~to~~, often reaching Switzerland and/or southern Germany~~stopping at the foot~~. These derechos commonly traverse north of the Alps ~~, or passing north of the Alps, matching most of the~~ or the Jura Mountains, aligning with the majority of warm-season events identified by Gatzen et al. (2020)~~; iii) a last type begins in the center or northeast of France and moves through the northern plains to the north-northeast towards the Benelux and /or Germany~~. Another set of derechos originates in central and northern France, extending through Belgium, Luxembourg, and the Netherlands, with some instances affecting western and northern Germany, and a few persistent events extending as far as Denmark and Sweden. Additionally, certain derechos initiate in the southwest of France or northern Spain, propagating in various directions from north to east.

After closely examining the spatial distribution of observed derecho frequencies in Figure 1b, we find a partial alignment with the European climatology of lightning in summer, as presented in Taszarek et al. (2020a). Notably, high activity is observed near mountain ranges such as the Pyrenees, the Alps, and the Massif Central, extending roughly to the southern and eastern regions of France, with relatively less activity in Brittany and Normandy, in the northwest. However, the highest frequency of derechos observed in the northeast of France diverges from this lightning climatology. Alternatively, when considering the climatology of severe wind events based on reports from ESWD in the same study, we find a more consistent correspondence. Severe wind events are indeed more frequent in central Europe, including Germany, and in the northeast of France and the Benelux. The 2022 derecho ~~that affected Corsica stands apart as it originated~~ impacting Corsica is distinctive, originating near the Balearic ~~islands~~ Islands in the Mediterranean ~~sea and no similar event is found, but there could have been similar events that we didn't detect as Corsica is a rather small isolated region and there is no or few weather stations at seait is difficult to detect such an event using our methodology. This~~ Sea with no comparable event identified. It's possible that similar events occurred but went undetected due to the limited number of weather stations over the sea. This particular derecho also affected ~~many other countriesincluding Italy and Austria so one should probably use station data from several Mediterranean countries , and/or include overwater stations like Gatzen et al. (2020) to study these derechos~~multiple countries, suggesting the potential for identifying similar events by focusing on Mediterranean countries like Italy and Spain.

~~We present histograms of~~ In Figure 2, we depict histograms illustrating the path length, duration, intensity, and month of occurrence of observed derechos~~on Figure 2. Most of the identified events are of low-end (48~~. The majority of identified events exhibit low (50 %) or moderate (~~45~~ 39 %) intensity~~with only 2 high-end intensity events (7 %)~~, with only 11 % classified as high intensity (Figure 2~~(a)). In comparison with~~ a). When compared with warm-season derechos identified by ~~Gatzen, we found smaller fractions~~ Gatzen et al. (2020), we note smaller proportions of moderate (54 %) and ~~high-end~~ high (14 %) intensity events and a larger fraction of ~~low-end~~ low-intensity events (32 %). However, ~~as previously noted, we assess the intensity using only weather stations reports in France in most of the cases, so by obtaining station data from other countries, one might obtain upgraded intensities~~given the limited sample size, we refrain from asserting the significance of this difference, a conclusion supported by a chi-squared test (Pearson, 1900) at the 0.05 level (p-value = 0.39). The average path length ~~is 660 km, similar~~ of derechos in France is 670 km, akin to the 620 km ~~found for~~ observed in Germany cases, and ~~we observe a large fraction of events having a rather~~ a substantial portion of events exhibit a relatively short path length (~~66 %) i.e. shorter than~~ 63 %) (Figure 2d), falling below the 650 km threshold ~~suggested by Corfidi et al. (2016) to revise the definitionof derechos, while medium (650 $\leq$ length $\leq$ 950 km) and long path length (> 950 km) have about the same fraction (17 % or 5 events each). We observe consistent results for the durationof the events~~ proposed by Corfidi et al. (2016) for revising derecho definition. Consistent results emerge for event duration, with a majority ~~of duration lower than 7 hours . From these results,~~ lasting less than 6 hours (Figure 2c). These findings suggest that derechos in France are both less frequent and ~~intense than derechos~~ less intense compared to their counterparts in the USA (~~about~~ approximately 10 per year)~~as was also noticed in Germany(Gatzen et al., 2020). Regarding the start time~~ , aligning with observations in Germany.

Examining the start times of derechos (~~histogram not shown~~Figure 2e), we ~~observe similar results as Gatzen et al. (2020) with a peak at near noon and a second one in the end in the afternoon with however a shift of the late afternoon peak later~~

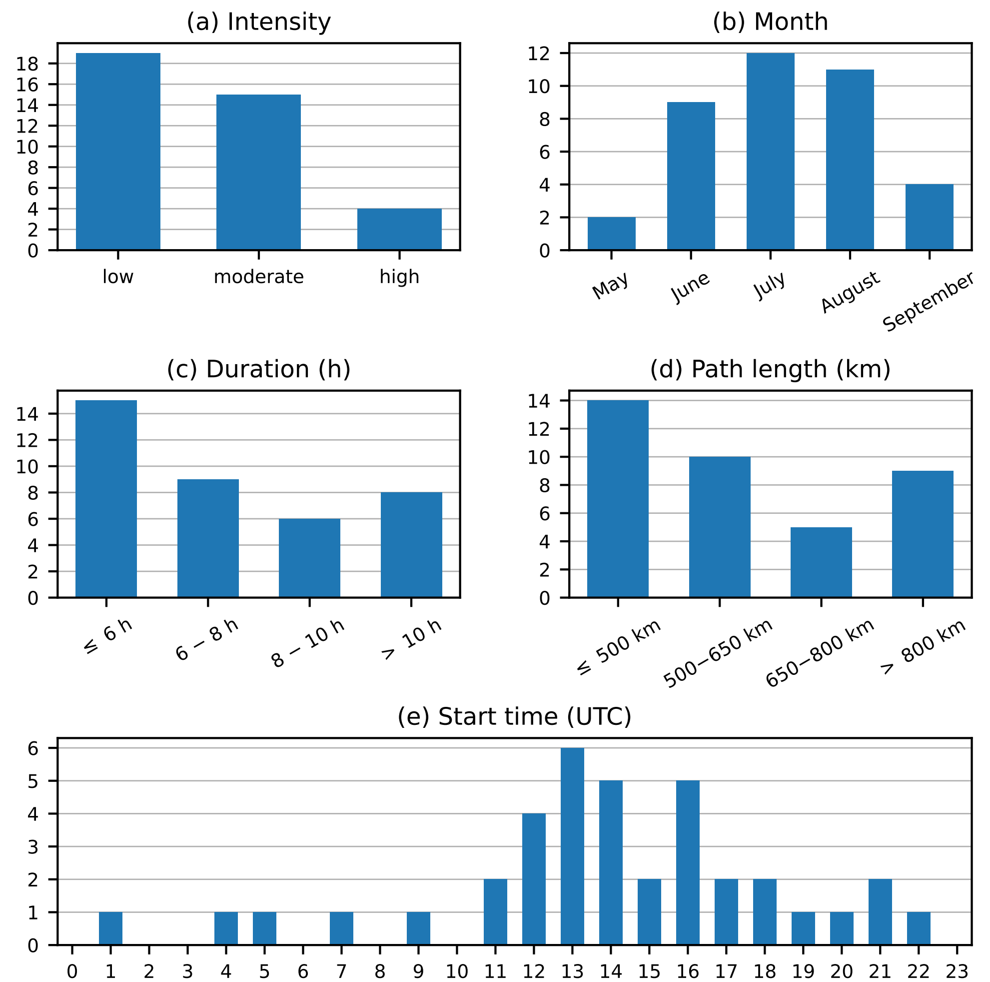

Figure 2. Statistics of observed warm-season derechos over France between 2000 and 2022. (a) Intensity defined from the number of reports exceeding given wind gust speed thresholds (high : at least 3 reports $> 38\,\mathrm{m\,s^{-1}}$, moderate : at least 3 reports $> 33\,\mathrm{m\,s^{-1}}$, low : all remaining events). (b) Path length of derechos computed from the distance between first and last severe wind gust reports. (c) Duration defined as the elapsed time between the first and last reports. (d) Month of occurence.

in the day (between 16:00 and 17:00 compared to between 15:00 note similarities with Gatzen et al. (2020), observing most events initiating between late morning and late afternoon, peaking around midday and again in the mid-afternoon. Notably, we observe a higher occurrence of events commencing in the evening and during the night compared to Germany. However, these differences lack statistical significance due to small sample sizes. The frequency of derechos varies considerably from year to year, reaching peaks of up to 7 events in 2018 and 16:00 in Germany) and more events starting in the night or the late evening. The derecho frequency is very dependent on the particular year as we observe up to 5 events in a single year 5 events in 2003, or 4 events in 2018 while we observe no events for some years while certain years experience no recorded events (2002, ~~2007,~~ 2008, ~~2016,~~ 2017). ~~Some events also happen successively as observed in Germanyby Gatzen et al. (2020) with two successive events on~~ Successive events also occur, mirroring observations in Germany, such as the consecutive events on July 26 and 27~~July~~ , 2013, ~~on~~ June 4 and 5~~June~~ , 2019~~or on~~ , or June 19 and 20~~June 2021 for instance. Interestingly, we do not~~ , 2021. Similar to findings in Germany (Gatzen et al., 2020) and the USA (Coniglio and Stensrud, 2004), we observe a peak ~~of occurrence in Julyas for derechos in Germany or USA Coniglio and Stensrud (2004), but similar occurrence frequency between July and August (34 % in each month). This is probably linked to the near presence of Mediterranean sea and Atlantic Ocean that are still a sufficient source~~ in derecho occurrences in July. However, in contrast to Germany, we still find high activity in August and we find four events occurring in September. While the distribution appears to lean more towards the late season compared to Germany, this difference lacks statistical significance based on a test using a bootstrap procedure. If this discrepancy were to be validated with larger sample sizes, it could potentially be attributed to the proximity of the Mediterranean Sea. Its warm waters continue to serve as abundant sources of moisture and heat late in the season~~to enable~~ , fostering significant instability and the development of severe convective storms ~~while this is not the case far inland like in Germany of the Great Plains in the US. We indeed observe that 8 out of 10 events occurring in August, have initiated in the south, either close to the Bay of Biscay or the Mediterranean sea. It is indeed well known that~~ (Taszarek et al., 2020a). Notably, southern France is ~~prone to~~ renowned for experiencing extreme convective rainfall episodes ~~in~~ during the fall season ~~Fumière et al. (2020); Ribes et al. (2019); Taszarek et al. (2019). This suggests we should perhaps include the month of September, and possibly October in the warm-season for studying derechos in southern Europe in future studies~~(Fumière et al., 2020; Ribes et al., 2019; Taszarek et al., 2019).

~~Statistics of observed warm-season derechos over France between 2000 and 2022. (a) Intensity defined from the number of reports exceeding given wind gusts speed thresholds (high : at least 3 reports $> 38\,\mathrm{m\,s^{-1}}$, moderate : at least 3 reports $> 33\,\mathrm{m\,s^{-1}}$, low : all remaining events). (b) Path length of derechos computed from the distance between first and last severe wind gusts reports. (c) Duration defined as the elapsed time between the first and last reports. (d) Month of occurence.~~

3.2 Results of attribution for the 18 August 2022 derecho

~~Trajectory of 18 August 2022 derecho and position of severe wind gusts reports from Météo-France in Corsica colored by their timestamp. The triangles represent extremely severe wind gusts ($> 38\,\mathrm{m\,s^{-1}}$), the rectangle represent medium severe wind gusts ($> 33\,\mathrm{m\,s^{-1}}$) and the circles represent other severe wind gusts ($> 25\,\mathrm{m\,s^{-1}}$). The time stamp of the first and last reports idenfied from ESWD are shown in the title.~~

~~Attribution for the 18 August 2022 derecho storm. Daily mean zero-centered geopotential height anomaly (z500) (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 1950-1980(b) and factual 1992-2022(c) periods and corresponding 2-meter temperatures (f,g), daily precipitation rate (j,k) and wind speed (n,o). ΔZ500 (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), AMO (v) and PDO (w). The number of analogues per decade (blue) and its linear trend (black) in (x). 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.

As in Figure **??** but for daily maximum CAPE.

As in Figure **??** but for daily maximum DLS.

We begin by analyzing in detail the result We initiate our analysis by closely examining the outcomes of the attribution analysis using employing the analogues methodology for the 2022 Corsica derecho to show how the results in the different . This examination aims to illustrate the interpretation of results across various variables and metrics are interpreted. As described .

As detailed in Section 1, a MCS developed and moved to the northeast, affecting advanced northeastward, impacting Corsica, Northern Italy, Slovenia, Austria, and Czechia within 12 hours, with the production of strong a 12-hour timeframe. The event was marked by the generation of robust wind gusts along a 1000 km axis along with , accompanied by severe hail and heavy rainfall in some locations. For a detailed meteorological report, see for example ESSL. Figure 3 shows the wind substantial rainfall in specific regions. Wind reports from Météo-France in Corsica and the trajectory of the storm. storm's trajectory are depicted in Figure 3. The synoptic conditions during the storm featured a meridional circulation with a cut-off low situated over the Gulf of Lion in the south of France, as illustrated in Figure 4. This figure includes daily averaged maps of Z500 (a), 2 meter temperature (b), total precipitation (c), and wind speed (d), along with daily maximum maps of CAPE (e) and DLS (f). Notably, we observe exceptionally high values of daily maximum CAPE and DLS along the storm's path, particularly over the Mediterranean Sea. These observations underscore the highly favorable conditions that contributed to the initiation of this particularly severe storm. For a comprehensive meteorological report, refer to ESSL.

Figure **??** shows 5 presents the results of the attribution study of focusing on the synoptic configuration associated with the episode. The Z500 field of the event (Figure **??**a) has been used for the search of 29 analogues for 4a) served as the basis for identifying 37 analogues for both the counterfactual and factual periods. Their average is displayed respectively in **??**b,c). We observed some , with their averages displayed in Figure 5a,b. Upon scrutiny, we observe no significant changes in the circulation pattern , namely a relative deepening of the low pressure system on the North Sea and a strengthening of the Eastern European high pressure system which reinforces the gradient and thus the mid-level wind downstream of the cut-off low. This change is consistent with higher temperatures over Eastern Europe while it is difficult to make any statement about which is one is the cause or the consequence. We also observe significant increase of temperature around the Mediterranean sea with no significant change over the sea itself for which one should probably look preferably at sea surface temperatures to see a signal. We observe a significant decrease of (Figure 5c). Notably, there is a pronounced increase in 2 meter temperature across most of Europe, particularly over the Mediterranean Sea. Concurrently, there is a substantial reduction in precipitation over Northern Italy and , contrasting with a significant increase in northeastern Europe which could be partly explained by the shift in the atmospheric flow. The same results are found for EOBS dataset (figures provided in supplementary material). When examining Eastern Europe and certain regions of the Mediterranean Sea (Figure 5g,h,i). These findings are consistent with results from the E-OBS

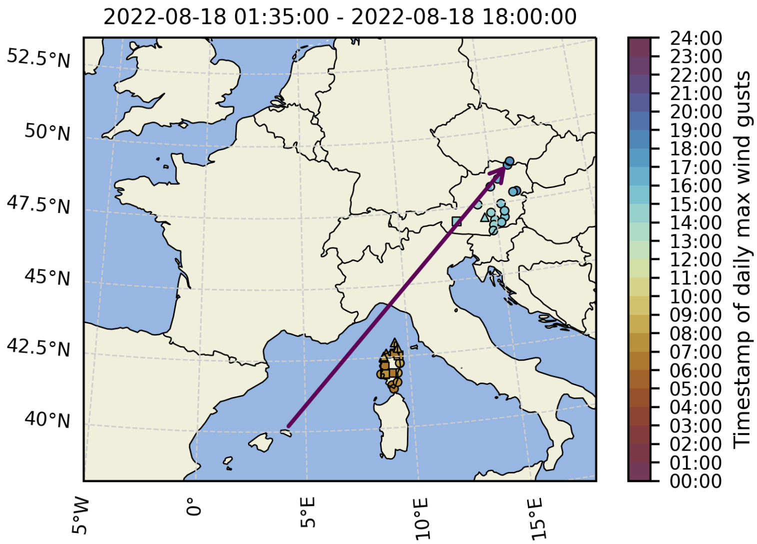

Figure 3. Approximate path of 18 August 2022 derecho and locations of severe wind gust reports from Météo-France and ISD colored by their timestamp. The triangles represent extremely severe wind gusts ($> 38\,\mathrm{m\,s^{-1}}$), the rectangles represent medium severe wind gusts ($> 33\,\mathrm{m\,s^{-1}}$) and the circles represent other severe wind gusts ($> 25\,\mathrm{m\,s^{-1}}$). The time stamp of the first and last reports, included those from ESWD are shown in the title.

dataset for temperature and precipitation (Figures S2 and S3 provided as supplementary materials). Analysis of daily maximum CAPE (Figure ??),we observe a significant increase 5m,n,o) reveals a significant surge over the Mediterranean, matching well with the very large values observed in aligning closely with the exceptionally high values observed on 18 August 2022. We note It's worth noting that ERA5 values for CAPE are unrealistically large exhibits an unrealistic spike for the 2022 derecho (locally > 5000 J/kg), which is a known issue, local values exceeding 5000 $\mathrm{J\,kg^{-1}}$ on Figure 4e), a known common issue highlighted in ERA5 documentation. As for On the other hand, the examination of deep layer shear ??,we find (Figure 5p,q,r) shows no significant signal along the path of the MCS.

The quality of the analogues (Figure ??q) shows that this

The evaluation of analogue quality (Figure 6a) indicates that the observed circulation is relatively common when compared to the rest of the analogues with no changes in the two periods. We do not detect visible changes in predictability D (Figure ??r) nor Although we do not observe a significant change in persistence Θ (Figure ??s6c) relative to the counterfactual world.

The seasonal occurrence of analogues (Figure ??t) is quite consistent with the months of thunderstorm occurrence in this area, with a maximum during August; however, we observe a small shift from June towards July.

The changes in ENSO (Figure ??u)are not statistically significant while AMO distributions have a significant , there is an apparent increase in the local dimension D (Figure 6b) in the recent past, signifying a decrease in the predictability of this pattern. Regarding the ENSO, NAO, PDO, EA and SCAND changes (Figure 6d,e,f,h,i), they are not statistical significance, whereas the AMO distributions exhibit a notable shift between the two periods (Figure ??v) and so do the Scandinavian

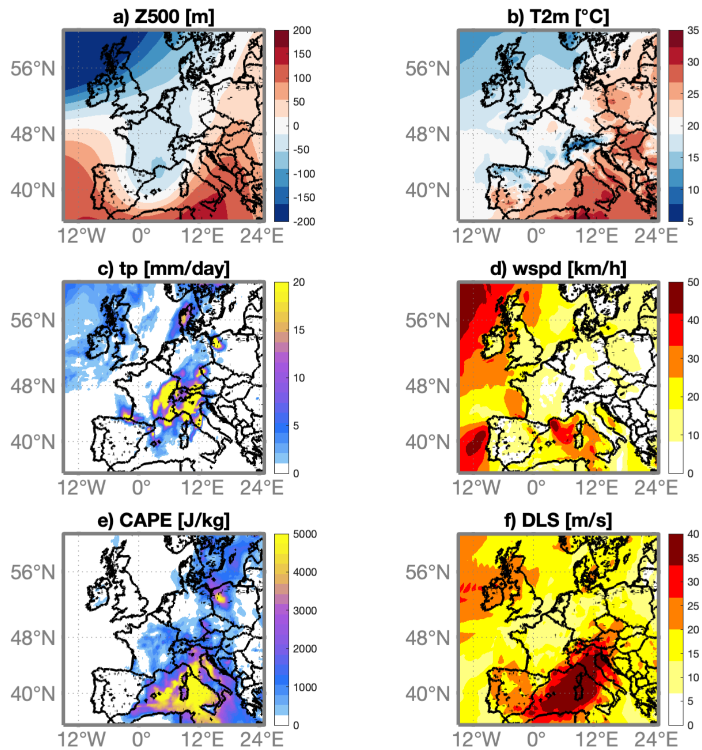

Figure 4. Daily averaged maps of zero-centered geopotential height anomaly at 500 hPa (a), 2 meter temperature (b), total precipitation (c), wind speed (d), CAPE (e) and DLS (f) for the 18 August 2022.

pattern (SCAND) (no shown here)suggesting a possible role of the 6g), suggesting a potential role of natural variability in accounting for explaining the observed changes. When comparing the patterns A thorough comparison of sea-level pressure, surface temperatureand precipitation , and precipitation patterns characteristic of AMO in Europe (Zampieri et al., 2017) with the patterns of changes found here , we find a very good agreementsuggesting that changes identified here reveals a remarkable agreement, supporting the notion that the AMO might be the major factorexplaining the observed changes. Finallya significant influencing factor. The seasonal occurrence of analogues (Figure 7a) aligns well with the months of lightning and severe wind events in this region (Taszarek et al., 2020a), peaking between August and September, with no significant shift in seasonality observed between the two periods. Lastly, when computing analogues for the whole entire period and counting their frequency per decade, we observe no significant trend (Figure ??wno discernible trend emerges (Figure 7b).

In summary, our analysis indicates that there is no significant change in the circulation patterns between the past and present based on the best analogues of the Corsica derecho. However, it is noteworthy that the surface temperatures associated with the cut-off lows are higher in the current period. A prominent signal of increased CAPE is identified in the present climate, which, with unchanged circulation, can be attributed to the exceptionally high temperature of the Mediterranean Sea. These findings align with the recent research by González-Alemán et al. (2023), highlighting the pivotal role of elevated temperatures

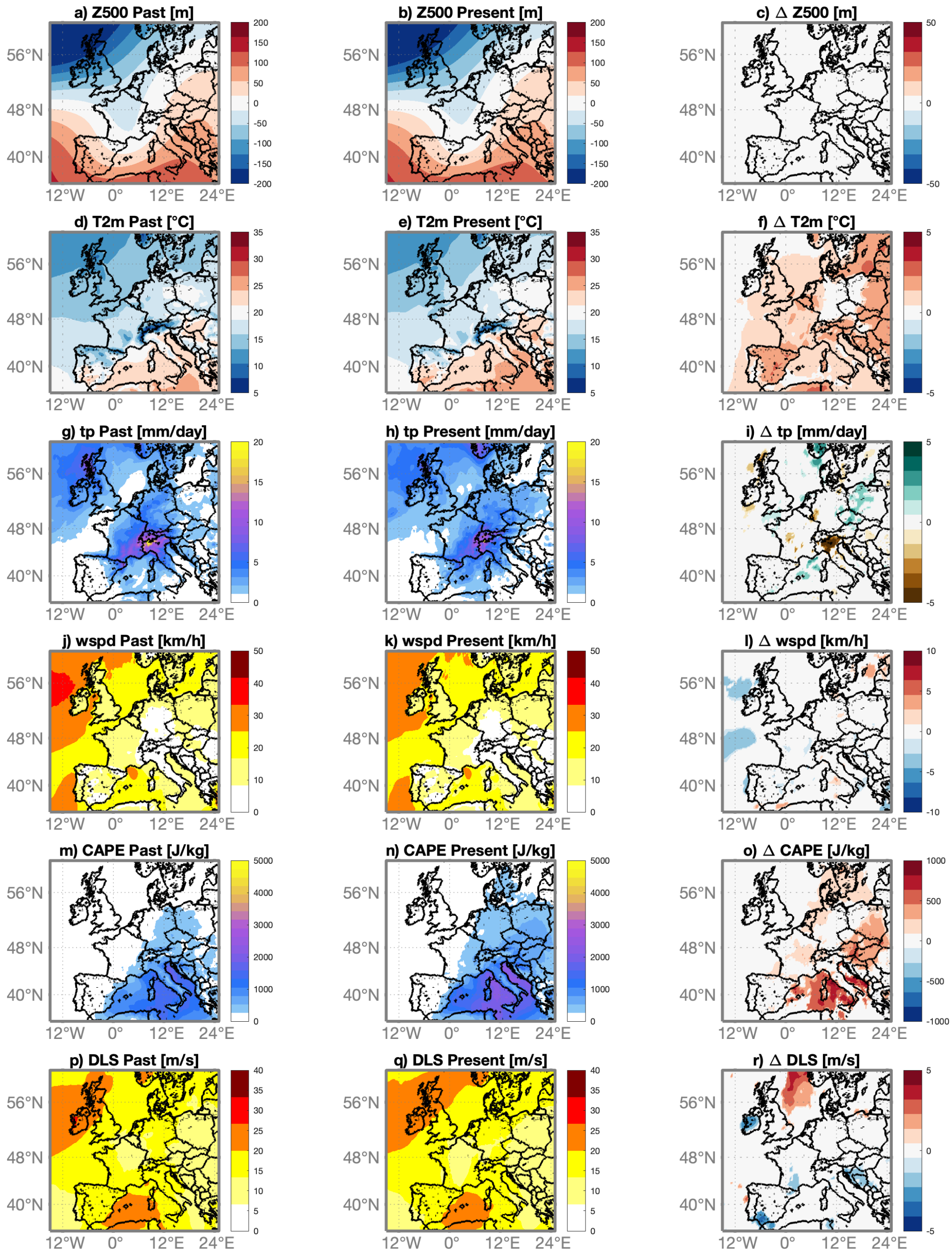

Figure 5. Attribution for the 18 August 2022 derecho storm. Average of the 37 analogues of daily mean zero-centered geopotential height anomaly at 500 hPa (Z500) found for the counterfactual [1950–1980] (a) and factual [1992–2022] (b) periods and corresponding 2 meter temperatures (T2m) (d,e), daily total precipitation (tp) (g,h) and wind speed (wspd) (j,k). Changes in the corresponding variables: ΔZ500 (c), ΔT2m (f), Δtp (i) and Δwspd (l) between factual and counterfactual periods (colored-filled areas show significant anomalies with respect to the bootstrap procedure).

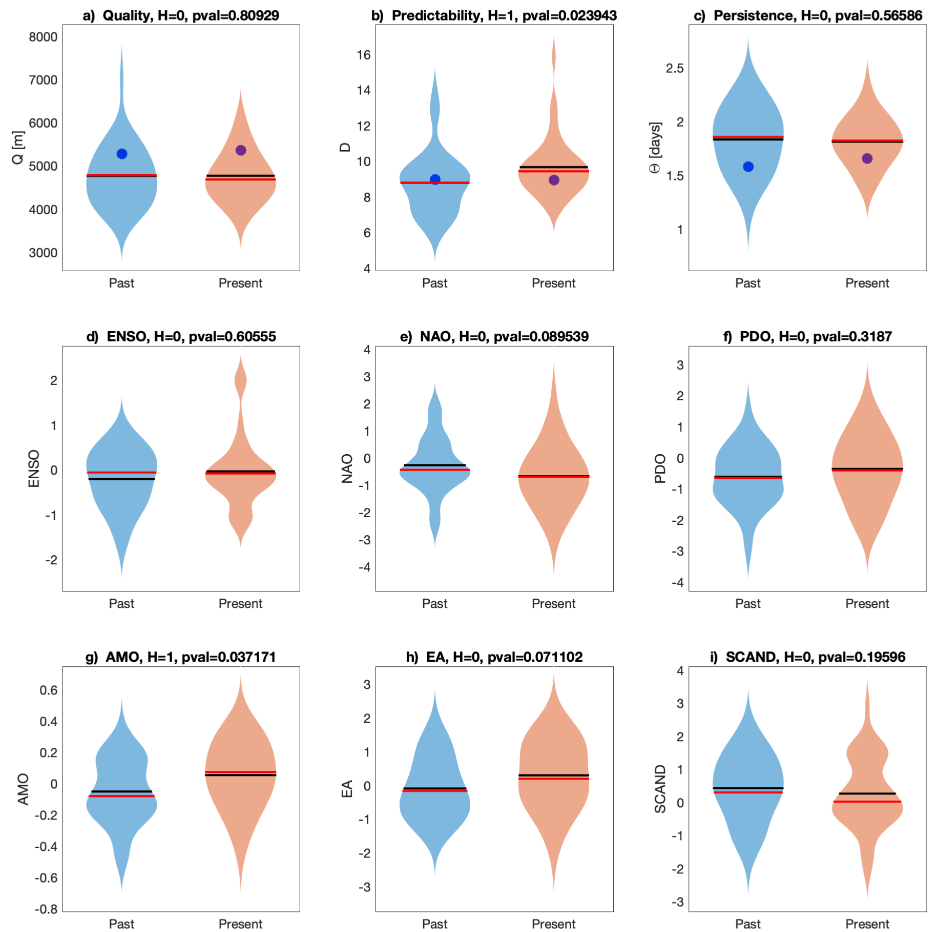

Figure 6. Violin plots for counterfactual (blue) and factual (orange) periods for the analogues Quality Q (a) the Predictability index D (b), the Persistence index Θ (c). Violin plots for counterfactual (blue) and factual (orange) periods for ENSO (u), AMO (v) and PDO (w). Values for the day of the event are marked by a dot. Horizontal black and red lines lines respectively represent the empirical mean and median of the distributions. Titles in (a–i) report the results of the Cramér-von Mises test (H) at the 0.05 significance level (H=0 implies that the distributions are compatible and H=1 that they are different) and the p-value (pval).

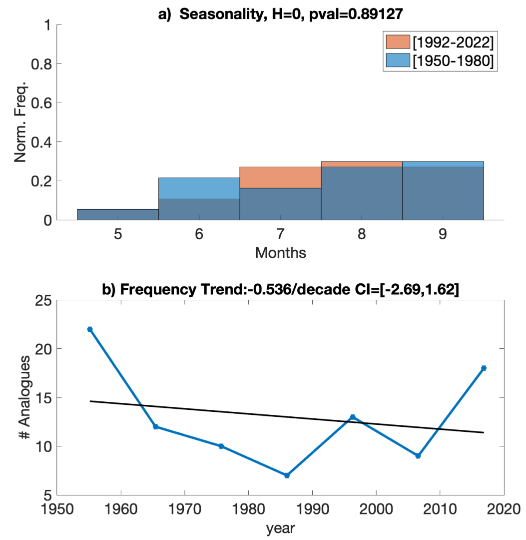

Figure 7. (a) Distribution of analogues in each month for the daily mean Z500 map of 18 August 2022. The title report the results of the test (H) at the 0.05 significance level and the p-value (pval). (b) Number of analogues per decade (blue) and its linear trend (black). the title includes the value of the linear trend slope and its confidence interval (CI) in square brackets.

in the Mediterranean Sea, characterized by anomalies surpassing +3°C during the summer compared to the seasonal values of 1990–2020, in influencing the development and intensity of the MCS responsible for the 18 August 2022 derecho. However, our analysis underscores the possibility of the Atlantic Multidecadal Oscillation (AMO) contributing to heightened near-surface temperatures and CAPE.

3.3 Overall changes in synoptic patterns and environmental proxies

For each event, we conduct a comprehensive analysis similar to the one performed for the 2022 event. The summarized results are presented in Table 2. Each event's entry indicates whether there is a significant change in the distributions of analogue quality (average Euclidean distance to the best 37 analogues), dynamical indicators (local dimension D and persistence Θ), and indices of natural climate variability (ENSO, NAO, AMO, PDO, EA, SCAND). For analogue quality (Q), local dimension (D), and persistence (Θ), we specify the sign of the change in the mean value using "+" for an increase, "-" for a decrease, and leave the cell blank if there is no significant change. For atmospheric variables or parameters (T2m, tp, using E-OBS, and CAPE and DLS, using ERA5), we apply the same notation. For climate variability indices (ENSO, NAO, AMO, PDO, EA, SCAND), we mark "1" when a significant change in the distribution between the two periods is observed and leave the cell blank otherwise. The same notation is used to indicate significant changes in the Z500 field (from ERA5), which may exhibit complex alterations in synoptic configurations, such as a dipolar or tripolar structure translating into changes in atmospheric flow intensity and/or direction. We also evaluate the significance of potential frequency trends (Trend) and seasonality shifts

(S. shift), marking “+” or “-” for positive or negative trends and for shifts towards late or early months of the warm season, respectively.

For each event, the same figures presenting the results of the attribution as for the 2022 event are provided in supplementary material. The overall results are summarized in Table 2. We show for each event whether there is a significant change or not in the distributions of analogues quality (average Euclidean distance to the best 29 analogues), dynamical indicators (local dimension D and persistence Θ) and indices of factor of natural variability (ENSO, NAO, AMO, PDO, EA, SCAND). For the dynamical indicators of analogues quality (Q), local dimension (D) and persistence (Θ) and for the frequency trend we specify the sign of the change in the mean value by "+" for an increase or "-" for a decrease, and we left the cell blank in case of no significant change. For atmospheric variables or parameters (t2m, tpfor which we consider EOBS, and CAPEand DLS for which we use ERA5)we use the same notation. For natural variability indices, we put 1 when there is a significant change, and left the cell blank otherwise. We mark the same way significant changes in We identify good-quality analogues for all events, as the event-to-best-analogues distance falls within the distribution of its analogues (not shown). This ensures a meaningful comparison between analogues in the two periods. However, we consistently observe significant changes in the Z500 field which can feature complex changes in the synoptic configuration such as a dipolar or tripolar structure which translates into changes in the flow intensity and/or direction, including the jet stream.

For 38 field (89 %), emphasizing the need for caution when making attribution statements for observed changes in diagnostic variables (T2m, tp, CAPE, and DLS). Some of these changes might result from shifts in circulation patterns, making it challenging to attribute them directly to anthropogenic climate change (Faranda et al., 2023; Vautard et al., 2023). For 42 % of the events, we observe a significantly reduced notably decreased average distance (Q) of for each analogue compared to its own analogues, which might indicate indicating that these patterns are more common may be more prevalent in the recent period. However, this does not necessarily translates in a significant increasing trend frequency of the analogues. Indeed, there are only result in a substantial positive trend in analogue frequency. Only 5 events (17 %) for which we observe a significant increasing 13 %) display a significant positive trend in the frequency of their Z500 analogues. The values are between 1.7 and 2.4 , with trend values ranging between 1.4 and 2.3 analogues per decadewhich is lower in average than the trends observed in average for the Z500 increasing patterns in the North Atlantic and Europe found in Faranda et al. (2023). Two (2) of —a noteworthy change relative to the mean number of analogues per decade. While analyzing the relative frequency of analogue occurrence during the warm season, the increasing patterns observed here (associated with the 2019-06-04 and 2001-08-15 events) match well with the composite of Z500 increasing patterns observed in this study. The pattern features a low-pressure anomaly in the Eastern Atlantic, off the coast of Britanny creating a southwesterly over the British Isles, which resembles the Spanish Plume, and a cut-off low over Greece. This suggests that this pattern known for its association with severe convective weather might become more common in the future.

We observe opposite results depending on the event majority of results appear statistically insignificant. Nevertheless, in 3 cases, we note a relative increase in frequency during the late season coupled with a decrease in the early season, while an inverse tendency is observed in 3 other cases. We find limited significant results for the local dimension (D), which is a proxy of a proxy for predictability, with only three increasing and three 3 increasing and 4 decreasing cases. As for the Regarding

Table 2. Results of the attribution analysis. The columns respectively represent: Number: identification number for each derecho event; Q: analogue quality change: D: local dimension change; Θ: persistence change ; Trend: trend in the number of analogues per decades (+ for increase, - for decrease, blank for no trend); S. shift: seasonality shift in the frequency of analogues (- for significant shift towards the early season, + for shift towards the late season, blank for no shift); Z500 (ERA5): changes in the Z500 pattern (1 if there are significant changes, blank otherwise); T2m (E-OBS), tp (E-OBS), CAPE (ERA5), DLS (ERA5): changes in those variables fields near the MCS path; ENSO, NAO, AMO, PDO, EA, SCAND: changes in the distribution of those natural variability indices between the two periods.

Number	Q	D	Θ	~~Freq. trend~~ Trend	~~z500~~ S. shift	~~t2m~~ Z500	T2m	tp	CAPE	DLS	AMO	EA	ENSO	NAO	~~AMO~~ PDO	~~EA~~ SCAND
1		-			-	1	~~+~~	+		~~-~~	1	1	1	~~−~~1	1	
2	+					~~1~~	+	+	+			~~−~~1	~~−~~1		~~1~~	~~1~~
3				~~+~~		1	+	-	+		~~1~~		1		~~−~~1	1
4	-	~~-~~	-		~~1~~		+				1		1			~~1~~
5	-			+		1	+	~~−~~+	+	+	1	~~−~~1	1	~~1~~		1
6			+			1	~~−~~+	+	+	+		1	~~−−~~1	1	1	1
7	-				+	1	+	~~-~~	+		1		1	~~1~~		
8						1					1	~~−~~1	1		~~1~~	1
9	-					1	+	+	+	+	1		1			1
10			-		-	1		+	~~−~~-		~~−~~1		~~1~~			
11		~~+~~	+			1	+	+	+		1	~~1~~	1	1	~~−~~1	1
12	-					1	+	~~+~~-	+	~~−~~+	1	~~−~~1	1			~~1~~
13	-				+	1	+	~~−~~+	+		1					
14	-					1	+			-	1		1	1		
~~14~~ 15		+	-			1	+		+		1		1	~~−~~1		1
~~15~~ 16	~~-~~	-				1		+		~~+~~	1	1	1	~~1~~	1	~~1~~
~~16~~ 17						1		+	+		1		1	1		
18						1	+	-	+					1	1	
~~17~~ 19	-		~~-~~			1	+		~~−~~+	-	~~−~~1		~~1~~			1
~~18~~ 20		~~−~~+	-			1	+			-	1		1	~~1~~	1	
~~19~~ 21	-			+		1	+		+	+	1		1		1	
22	-	-				1	+		+		1		1		1	
~~20~~ 23	-					1				-						
~~21~~ 24						1	+	-		+	1		1			1
25	-					1	+	+	+				1			1
~~22~~ 26					+	1	+	-	+		1		~~+~~1			1
27	+		+			1	+	+	+	-			1		1	1
~~23~~ 28	-		~~-~~	+		1	+	~~−~~+	+		1					1
29	-		-	+		1	+	-	+				1	1	1	
~~24~~ 30	-			~~-~~		1	+		+	-	1					1
31	-		-				+		+	-	1		1		1	
~~25~~ 32		-	+		-	1		+		+	1		1		1	
33	-		-	+		1	+		+				1	1	1	
34		~~26~~	-			1	+		+	-				1	~~+~~	~~+~~
35	~~+~~					1	+		+	-	1		1			
~~27~~ 36			-			1	+	+	+		1	1	1	~~−~~1		
~~28~~ 37	~~+~~					1	+	+	+			1		~~−~~1		
~~29~~ 38		+				~~1~~	+	-	+		~~−~~1		~~1~~			~~1~~

~~Table showing the results of the attribution analysis with analogues. The columns are: Number: identification number for each derecho event; Q: analogue quality change: D: local dimension change; Θ: persistence change ; Frequency trend: trend in the number of analogues per decades (+ for increase, - for decrease, blank for no change); z500 (ERA5): changes in the Z500 pattern (1 if there are significant changes, blank otherwise); t2m (EOBS), tp (EOBS), CAPE (ERA5), DLS (ERA5): changes in those variables fields near the MCS path; ENSO, NAO, AMO, PDO, EA, SCAND: changes in the distribution of those natural variability indices between the two periods (1 if there~~

persistence (Θ), we ~~observe more often~~ more frequently observe a significant decrease ~~of persistence (30 %)of the patterns~~(24 %), while in ~~(7 %) we observe an increase of persistence.~~

~~Apart one event for each no good analogue can be found (event n°12, 25 May 2009) – as the distance of the event to the best analogues is in the upper tail of the distribution – we find good quality analogues for all the events, which means the comparison between the analogues in the two periods is meaningful. However, we almost always notice significant changes in the Z500 field which implies we must be very careful in making attribution statements for the observed changes on the diagnostic variables (t2m, tp, CAPE and DLS)~~11 % of cases, there is an increase in persistence.

For ~~most of the events (76 %)we observe an significant increase of temperature, as expected with anthopogenic climate changean we observe no case with~~ the majority of events (82 %), we observe a significant increase in temperature, in line with expectations of anthropogenic climate change. There are no cases with a significant decrease, while the remaining cases show no significant change. ~~We also find in almost half cases (48 %)an increase of precipitationwhile small fraction (17~~ In almost half of the cases (42 %), we observe an increase in precipitation, while a smaller fraction (18 %) shows a decrease~~of precipitation. An increase of precipitation volume is in line~~ . The increase in precipitation volume aligns with the projected ~~increase of~~ rise in extreme precipitation in Europe ~~Masson-Delmotte et al. (2021); Ribes et al. (2019), but one must keep in mind that here we are comparing~~ (Intergovernmental Panel On Climate Change (IPCC), 2023; Ribes et al., 2019). However, it's crucial to note that our comparison involves average situations for a given circulation pattern, which ~~do not necessarily each correspond to extreme precipitations events. In 69~~ may not necessarily correspond to each being an extreme precipitation event. In 74 % of the cases, we ~~notice~~ observe an increase in instability measured by CAPE~~and we don't find any decreasing case. This is in agreement with past findings about the increase of~~ , with only one instance of a decrease. This finding aligns with previous studies on the observed or projected rise in convective instability with global warming in Europe, particularly in the Mediterranean region ~~Taszarek et al. (2021b). There are less significant results for DLS , with 14 % of decreasing cases and 17 % of increasing cases~~(Rädler et al., 2019; Taszarek et al., 2021a, b; Pilguj et al., 2022). Results for DLS show fewer significant trends, with 24 % indicating a decrease and 18 % indicating an increase. These findings are consistent with the more modest and less frequent trends observed in vertical wind shear in the aforementioned studies.

As for the ~~influence~~ role of natural variability in ~~accounting for~~ contributing to these changes, we cannot ~~rule out~~ dismiss its influence on the observed ~~changes. The most frequent factors involved are in the decreasing order ENSO (69~~ shifts. Examining the factors in descending order of frequency, we find ENSO (74 %), AMO (~~62~~ 71 %), SCAND~~(45~~ , and PDO (both 37 %), ~~PDO (41~~ NAO (32 %), ~~EA and NAO (both 34 %) .~~

~~When looking at relative frequency of occurrence in the months of the warm season (see supplementary figures, not shown in the table),~~ and EA (24 %) as the studied variables. These results align with prior studies emphasizing the substantial impact of natural variability on convective activity in Europe (Casanueva et al., 2014; Tippett et al., 2015; Zampieri et al., 2017; Nobre et al., 2017; P . However, our findings suggest that ENSO might play a significant role in influencing convective environments, contrasting with Nobre et al. (2017), who reported a more limited impact of ENSO compared to NAO and EA on extreme precipitation in Europe. One potential explanation for the dominance of AMO and ENSO might lie in their longer typical time scales (ranging from annual to multidecadal), in contrast to teleconnection patterns like NAO, EA, and SCAND, which are more closely tied to the chaotic dynamics of the results are really case-dependant and it is thus difficult to make any general statement. More some patterns , we observe a relative increase of frequency in the late season with a decrease in earlier season and for some other patterns we observe an inverse tendency. More investigation would be needed to clarify those results, by e.g. making composites or clustering of the patterns with similar tendencies. atmosphere and exhibit shorter-term variations on time scale of the order of the week (Hurrell et al., 2003; Hurrell and Deser, 2010). By comparing composites of analogues over 31-year periods, we anticipate that the faster processes would be more effectively smoothed out, emphasizing the influence of longer-term variability.

4 Conclusions

In conclusion, the study provides In summary, this study presents a 23-year climatology of warm-season derechos in France between spanning from 2000 and to 2022. The eventshave been detected using wind gusts To detect events, we used wind gust reports from weather station data(primarily , primarily sourced from Météo-Franceand ESWD) and mapped with MCS detected using satellite imagery. We identified twenty-nine (29) eventsand analyzed their features in comparison , supplemented by data from ISD, DWD, and ESWD. Mapping was conducted using an MCS detection and tracking algorithm with satellite imagery, leading to the identification and analysis of thirty-eight (38) events. A comparative examination of their features was carried out, drawing parallels with climatologies in the USA and Germany. Similarly to the observed Similar to observed warm-season derechos in Germany, warm-season derechos in France are much notably less frequent and intense than those in the USA. Countrywide, we observe on average 1.26 derecho Nationwide, an average of 1.65 warm-season derechos occurs per year, while with the highest local frequency is observed in northeastern France with about 0.6 at 0.65 derecho per year in within a 200 km × × 200 km grid cell. The frequency per standardized grid cell is similar but slightly lower than , comparable to the maximum frequency observed in Germany. Another difference is that events are more frequent in August in France the proportion of short-lived low-end intensity events is larger. As in Germany, warm-season derechos are associated with southwesterly flow and most of the storms move in a northeastern direction. Derecho-producing MCS in the warm-season tends to develop primarily in the center north, the southwest and the east but not much in the west.

We also investigated the potential role Some distinctions include a frequency of occurrence leaning more toward the late season in France, with comparable frequencies of derechos in July and August, and a few events in September. Additionally, there is a larger proportion of low-intensity events in France compared to Germany. However, due to the small number of events, it is important to emphasize that these differences between the two countries cannot be considered statistically significant. Exploring the potential impact of climate change in modifying the characteristics of the on altering atmospheric circulation and environmental conditions associated with historical derechosthrough the , we compared analogues of circulation patterns defined by based on 500 hPa geopotential height . We compared the weather patterns in a relative between a relatively distant past (1950-1980) and in 1950–1980) and a more recent past (1992-2022). We observed significant increase of period (1992–2022). The analysis revealed a concurrent significant increase in 2 meter temperature and maximum daily CAPE, notably around the Mediterranean basin, and 2 m-temperature along with changes in the Z500 patterns for most events. Natural variabilitycannot be excluded in accounting for the observed changes, particularly the aligning with findings from other studies in Europe and expectations of a warming climate. However, attributing these changes is challenging due to accompanying shifts in circulation patterns represented by 500 hPa geopotential height. Additionally, natural variability, particularly from ENSO and AMO, for most events and further investigation is necessary to understand better the role of each of these factors and anthropogenic climate changecannot be ruled out as contributors to the observed changes.

It is important to note that this study has some limitations. Indeed, the methodology we used for the detection of derechos rely on The methodology employed for derecho detection introduces some limitations, relying on a semi-objective analysis , with a significant part of manual subjective decisionsnotably for that includes manual decisions, particularly in the selection of days prior checking for verifying the existence of associated MCS and mapping the wind gusts wind gust reports with the MCS. The use of radar data would be useful to better assess the characteristics of the detected MCS which is diffult to do with satellite imagery because of the limited temporal and spatial resolution. Alternatively, or in complement, one could use lightning datasets such as EUCLID Schulz et al. (2016) to check the existence and track convective systems. Moreover, we mainly used weather stations data from Météo-France, which limits the accuracy of While the primary weather station data from Météo-France, DWD, and ISD provides broad coverage, limitations arise in instances where ISD wind gust data is lacking in certain countries or during specific time periods. The study's scope excludes derechos in the detection near the national borders and while ESWD has proved very useful to provide severe wind gusts records and damage reports, it would be better to use other national station dataor international SYNOP stations to precisely assess the intensity of each event and to improve the detection procedure. It would also be desirable to have an automated detection algorithm for detecting derechos as a manual identification is laborious and implies many flaws. Finally, a cold season, and a comprehensive full-year climatology of derechos in France is still missing, and we could probably include the month of September in the warm-season for future studies. Based on the results and the limitations of this study, it is clear that further research is needed to better understand the statistics and dynamics of derechos and their potential link to climate change in France and Europe. Another area of focus could be gathering climatology remains unexplored. While exploring changes in synoptic conditions and convective environmental parameters, we aimed to estimate the potential impact of specific internal variability factors on large-scale conditions associated with derechos. However, our analysis does not achieve a precise understanding of the individual contributions of these factors and anthropogenic climate change to the occurrence of derecho-producing MCS. Additionally, the study does not consider potential influences from land use and land cover changes, surface variables like SST, and focuses exclusively on France, without extending its considerations to other regions.

To address these limitations, future studies could benefit from radar data (Huuskonen et al., 2014) and lightning datasets (Schulz et al., 20 to enhance detection accuracy and refine event definitions. The detection of derechos is arduous due to the collection of data from different sources, the volume of data to analyse and the manual identification procedure. Automation of derecho detection would prevent flaws due to subjectivity and improve efficiency. Additionally, more detailed observations and data on the on environmental conditions and dynamics associated with derechosusing e.g. proximity soundingsEvans and Doswell (2001); Gatzen et al. (202 , or model output from , using proximity soundings (Evans and Doswell, 2001; Gatzen et al., 2020), high-resolution reanalyses such as the forthcoming ERA6 or the analyses provided by non-hydrostatic convection permitting (Coppola et al., 2021)

~~weather modelssuch as WRF, ICON or AROME. Unfortunately we do not dispose of sufficiently long time series to use the existing data for the purpose of attribution.~~

~~Our attempt to analyse changes in synoptic conditions and convective environmental parameters characterizing instability (daily maximum CAPE) and wind shear (daily maximum 0-6 km wind shear or deep layer shear) and their potential links to natural variability and anthropogenic climate change has also some limitations and a more detailed analysis of the observed patterns associated with derechos is necessary to be able to make more convincing statements. This includes the clustering of the Z500 patterns to study similar patterns together and check if their trends are robusts. The study also does not take into account the potential impact of land use and land cover changes, as well as other surface variables including sea surface temperature (SST). The~~ weather models (Coppola et al., 2021), could offer deeper insights. In subsequent studies, a more comprehensive evaluation and quantification of the role of internal variability could be ~~better assessed and quantified in linking~~ attained by establishing connections between derecho occurrence and ~~the indices of those factors. These factorslikely play a role not only in creating more or less favorable environments as we have seen for the role of AMO in the 2022 derecho case, but also in modulating the frequency of large-scale atmospheric circulation patterns favorable for the development of MCS which we haven't investigated. As for the detection of changes in physical variables and environmental parameters, we decided to compare composite fields of daily mean 2 meters-temperature, precipitation, and daily maximum CAPE and DLS but we could consider examining changes in percentiles like Taszarek et al. (2021a) to focus on changes in extreme values, as changes in average conditions can not trivially be linked with changes in extremes. We could also include more convective parameters such as convective inhibition (CIN) or relative humidity. Additionally, the study mainly focused on France and surrounding countries and the results may not be extended to other regions~~indices of these factors. The potential societal impact of derechos on society (Ashley and Mote, 2005), infrastructure, and people's safety~~is another area of interest (Ashley and Mote, 2005), that one could investigate in Europe, including the link between derechos and~~ , including their correlation with other extreme weather events~~such as flash floods and heatwaves to gain insightsinto the potential impact of derechos on society.~~ , would be another interesting aspect to consider. While this study contributes valuable insights, continued research is essential to advance our understanding of the climatology, dynamics, and potential links to internal variability and climate change of derechos in France and Europe.

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.

The Python FLEXible object TRacKeR (PyFLEXTRKR) algorithm developed by Feng et al. (2023a) and is available at https://github.com/FlexTRKR/PyFLEXTRKR.

Other analysis codes and the database of warm-season derechosin France are available upon requests from the authors.

Data availability. ERA5 reanalysis data is available on the Copernicus Climate Change Service (C3S) Climate Data Store https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset. The ERA5 data for attribution have been downloaded from the preprocessed http://climexp.knmi.nl. The E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, is available from the ECA&D project (https://www.ecad.eu). The GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06 and the NCEP/CPC L3 Half Hourly 4km Global (60S - 60N) Merged IR V1 datasets are available from the Goddard Earth Sciences Data and Information Services Center (GES DISC) respectively at https://doi.org/10.5067/GPM/IMERG/3B-HH/06 and https://doi.org/10.5067/P4HZB9N27EKU. Weather stations data from Météo-France is available on free request for research purpose from https://publitheque.meteo.fr/. The Integrated Surface Database (ISD) from the National Oceanic and Atmospheric Administration (NOAA) is accessible from https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database. The European Severe Weather Database (ESWD) from European Severe Storms Laboratory is accessible at https://eswd.eu/. Data from German Weather Service (DWD) weather stations is accessible at https://cdc.dwd.de/portal).

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 system—in our case successions of daily Z500 latitude–longitude maps — corresponding maps—corresponding to a sequence of states on the attractor. For a given point ζ in phase space (e.g., a given Z500 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 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 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 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. (2019).

Author contributions. LF performed the detection and tracking of derechos and the subsequent analysis. DF performed the attribution analyses. Both authors contributed to discuss the results and write the manuscript.

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