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Major Role of Marine Heatwave and Anthropogenic Climate Change on a Giant Hail Event in Spain

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Key Points:

- Unprecedented hailstones in Spain (up to 12 cm) caused widespread damage and one fatality
- A record-breaking marine heatwave enhanced the strong hail-favorable environment
- Novel demonstration of an extreme hailstorm event attribution to anthropogenic warming

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

A severe hailstorm that occurred in Spain on 30 August 2022, caused material and human damage, including one fatality due to giant hailstones up to 12 cm in diameter. By applying a pseudo-global warming approach, here we evaluate how a simultaneous marine heatwave (and anthropogenic climate change) affected a unique environment conductive to such giant hailstones. The main results show that the supercell development was influenced by an unprecedented amount of convective available energy, with significant contributions from thermodynamic factors. Numerical simulations where the marine heatwave is not present show a notable reduction in the hail-favorable environments, related mainly to modifications in thermodynamic environment. Our simulations also indicate that the environment in a preindustrial-like climate would be less favorable for convective hazards and thus the hailstorm event would likely not have been as severe as the observed one, being possible to perform a novel attribution of such kind.

Plain Language Summary

In August 2022, northeastern Spain faced a damaging hailstorm with hailstones up to 12 cm, causing significant harm and one fatality. This study examined how hail-favorable environments were modified by a marine heatwave and human-induced climate change. Numerical simulations show that the storm's intensity was influenced by abundant atmospheric energy and moisture from the warm sea, partly influenced by human-induced warming. When the warm sea factor was excluded from the simulations, hailstones were smaller. These findings emphasize the role of human-induced climate change and warm sea surface temperature events in intensifying extreme and high-impact weather events like hailstorms.

1. Introduction

On 30 August 2022, a severe hailstorm event had a large socioeconomic impact on the Gerona province (northeastern Spain), with hailstones reaching up to 12 cm (Figure 1a), never documented before in Spain. Damage to roofs, cars and croplands was very serious. The hailstorm injured 67 people, including one fatality, which was the first direct hail fatality in Europe since 1997 (Pucik, 2022). The vast majority of hail cases with diameter larger than 5 cm are related to supercell thunderstorms (Blair et al., 2017; Kumjian & Lombardo, 2020). Supercells and hailstorms pose a recurrent threat over Europe (Dahl, 2006) resulting in substantial economic losses, societal impacts, and hazards to aviation safety (Antonescu et al., 2017; Kunz et al., 2020; Nisi et al., 2016; Púčik et al., 2019). There is growing evidence that the ongoing climate change is having a relevant impact on the frequency and intensity of severe convective events involving hail (Ashley et al., 2023; Battaglioli et al., 2023; Brimelow et al., 2017; Raupach et al., 2021).

Climate change alters atmospheric circulation patterns (Herrera-Lormendez et al., 2023) and increases sea surface temperatures (SST), notably in the Mediterranean Sea (Pastor et al., 2020; Pastor & Khodayar, 2023), contributing to significant high-impact weather events (González-Alemán et al., 2023; Lau et al., 2016; Ludwig et al., 2013; Meredith et al., 2015). The increase in SST influences intensity and frequency of marine heatwaves (MHW). MHW, defined as a prolonged period of anomalously high SSTs, typically lasting five or more days (Hobday et al., 2016), leads to increases in low-level moisture. This can consequently contribute to greater potential instability that offsets expected reductions in deep-bulk wind shear on observed rawinsonde profiles (Taszarek, Allen, Brooks, et al., 2021; Taszarek, Allen, Marchio, & Brooks, 2021) expected in future climate

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scenarios (Lepore et al., 2021)—an important ingredient determining organization and severity of convective storms (Brooks et al., 2003; Del Genio et al., 2007; Muramatsu et al., 2016; Peters et al., 2019; Trapp et al., 2007, 2009). In the western Mediterranean, MHWs significantly impact air temperature and summer precipitation (Serrano-Notivoli et al., 2023). Thus, the SST influence on localized convective hazards like tornadoes, giant hail, or severe wind gusts are gaining attention (Ashley et al., 2023; González-Alemán et al., 2023; Miglietta et al., 2017).

This study focuses on the analysis of the above-mentioned giant hail event, which developed during a record-breaking MHW in the Mediterranean Sea. The aim is to analyze the hail-favorable environment, its relationship with the MHW and the possible effects of the anthropogenic climate change (ACC) on the hailstone size. For this purpose, we have used the pseudo-global warming approach (PGWA; Schär et al., 1996). This approach has been applied to extreme events before, such as hurricanes (Patricola & Wehner, 2018; Reed et al., 2020, 2021), heavy rainfall (Kawase et al., 2022) and a historic derecho in the Mediterranean basin (González-Alemán et al., 2023).

2. Data Sets and Methodology

2.1. Observational Data Sets

The Spanish Supercell Data set (Martín et al., 2021) and the European Severe Weather Database (ESWD; Dotzek et al., 2009) observations are here used to analyze a climatological background and uniqueness of the Gerona giant hail event. The Spanish Supercell Data set (Calvo-Sancho et al., 2022; Martín et al., 2021) encompasses the period from 2011 to 2022 with a total of 286 documented supercell observations. The data set includes Supporting Information S1 to the events whenever available, such as hail diameter or tornado intensity. For the purposes of this study, only hail with a diameter larger than 5 cm is considered. In total, 57 large hail reports from the Spanish Supercell Data set are evaluated. The ESWD is Europe's main severe weather reports data set (Dotzek et al., 2009). This data set uses quality control (QC) classes to assess the accuracy and reliability of reports. For this study, only hail reports with a highly reliable status of QC1 (report confirmed by a reliable source) and QC2 (scientific case study) were included in the analysis. Only hailstones larger than 5 cm are considered for the period from 1940 to 2022 across continental Spain and the Balearic Islands. In total, 99 large hail reports from ESWD are included in this work.

In both observational data sets, 2022 is excluded to avoid incorporating Gerona giant hail in statistical comparisons. Probability density functions (PDF) are applied on climatological hail data to show the rarity of Gerona's event.

2.2. Large Hail Proxy

Taszarek, Allen, Groenemeijer, et al. (2020), Taszarek, Allen, Púčik, et al. (2020), Taszarek, Allen, Marchio, and Brooks (2021), and Taszarek, Allen, Brooks, et al. (2021) developed three environmental proxies (thunderstorm, severe thunderstorm and tornadic thunderstorm) that were used to construct modeled severe storm frequency and their accompanying long-term trends across Europe and the United States. Based on their methodology, here we introduce a new proxy to study very large hail environments. This proxy consists of a 5 cm threshold for the Hail Size Index (HSI; Czernecki et al., 2019). HSI was previously applied in Papavasileiou et al. (2022) and Poręba et al. (2022). Furthermore, an additional condition is added using the ERA5 hourly convective precipitation rate (>0.25 mm/hr) as a proxy for convective initiation (Taszarek, Allen, Brooks, et al., 2021; Taszarek, Allen, Groenemeijer, et al., 2020; Taszarek, Allen, Marchio, & Brooks, 2021; Taszarek, Allen, Púčik, et al., 2020). These restrictions are here considered as a proxy for very large hail to evaluate the spatiotemporal distribution and the influence of ACC on very large hailstorms.

The non-parametric Mann-Kendall trend (Kendall, 1975; Mann, 1945) and Sen slope tests (Sen, 1968) are applied to identify statistically significant trends in the number of hours per year for the large hail proxy at 95% confidence.

2.3. WRF Model

Numerical simulation experiments are achieved by running the widely used and highly verified Weather Research and Forecasting (WRF) model, version 4.2 (Skamarock et al., 2019). The model was configured with three one-

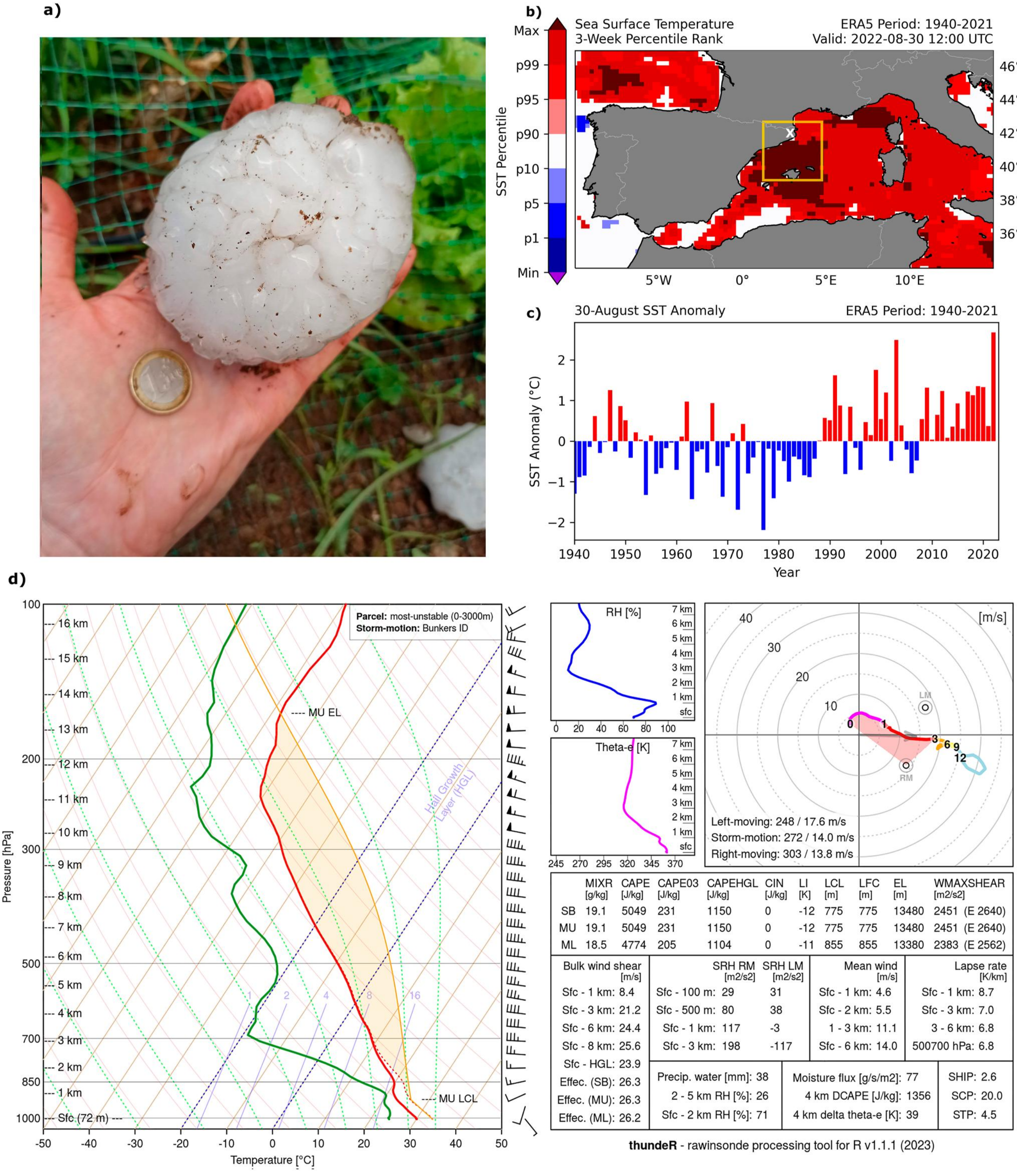

Figure 1. (a) Photography of a hailstone collected on 30 August 2022, in Forallac (Gerona province). Source: x.com/Morgana_50. (b) Western Mediterranean SST 3-week percentile rank of 30 August 2022, for the period 1940–2021 derived from ERA5 reanalysis. The white cross indicates the location of the giant hail event, and the yellow square indicates the area where the SST anomaly is calculated. (c) Time series of SST anomalies averaged over the yellow square area and period in (b). (d) Skew-t profile and hodograph for a Forallac's proximity profile derived from ERA5 reanalysis for 30 August 2022, 16:00 UTC, 42°00′N, 003°00′E. Processed using *thundeR* package at http://rawinsonde.com/ERA5_Europe/.

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way nested domains with horizontal resolutions of 9-3-1 km. The simulations are conducted for a 24-hr period, setting a 6-hr spin-up and the initialization time at 00:00 UTC on 30 August 2022. The initial/boundary conditions are obtained from the ECMWF's ERA5 reanalysis (Hersbach et al., 2020) with a 0.25° horizontal resolution and 1 h temporal resolution. More information on the WRF model configuration is provided in Supporting Information S1.

2.4. CMIP6 Models

The Coupled Model Intercomparison Project Phase 6 (CMIP6; O'Neill et al., 2016) is considered in this survey. Instead of only using a single climate model to derive climate conditions, herein we use three climate models from CMIP6 to take into account climate uncertainty; namely, EC-EARTH3, CESM-WACCM, and MRI-ESM2-0. These models include a pre-industrial control simulation (hereafter piControl) from 1850 to 1879, a historical simulation (hereafter HIST) from 2007 to 2014, and a Shared Socioeconomic Pathway 5–8.5 scenario (hereafter SSP5-8.5) from 2015 to 2036.

2.5. Pseudo-Global Warming Approach

The PGWA adds a climate perturbation signal to the reference conditions for the period of interest (Brogli et al., 2023; Sato et al., 2007; Schär et al., 1996). The PGWA is here applied to analyze the ACC signal contribution to the giant hail development associated with the supercell, considering the piControl and SSP5-8.5 simulations from the CMIP6 climate models. To apply the PGWA, several prognostic variables from ERA5 initial and boundary conditions are modified, that is, temperature, geopotential height, relative humidity, wind components, 2-m temperature, skin temperature, surface pressure and sea surface temperature. Although aerosol emission is an important source of uncertainty in hailstone growth, herein we did not quantify the aerosol contribution changing the current concentration with a preindustrial approximation because we wanted to focus on ACC thermodynamical effects. First, the difference ($\Delta \in$ Equation 1) between two climate periods, 1850–1879 and 2007–2036, is defined for each climate model used. The period 2007–2036 is selected to use a climate timeframe where the giant hail event is centered into a 30-year climatic period.

$$\Delta = \overline{(1850 - 1879)} - \overline{(2007 - 2036)} \tag{1}$$

An ensemble of Δ from different models ($\overline{\Delta}$ in Equation 2) is computed. This is used to perturb the ERA5 initial and boundary conditions to provide a preindustrial context, namely ERA5' (Equation 3), which is used as initial and boundary conditions in the WRF simulations.

$$\overline{\Delta} = \overline{\Delta_{\mathrm{EC-EARTH3}} + \Delta_{\mathrm{CESM-WACCM}} + \Delta_{\mathrm{MRI-ESM2-0}}} \tag{2}$$

$$\mathrm{ERA5}' = \mathrm{ERA5} + \overline{\Delta} \tag{3}$$

Considering this methodology and to analyze the impact of the ACC on this hail event, the WRF model is used to simulate the supercell development. Several experiments are carried out: WRF-Control (the control experiment with the non-pertubed ERA5 initial/boundary conditions) and WRF-Preindustrial (using the perturbed ERA5'). Additionally, a WRF-ERA5CLIM experiment is included, where the SST of the event is substituted by the climatological SST to study the MHW sensitivity.

2.6. Analyzed Convective Parameters

We use the ERA5 reanalysis to study climatological aspects of HSI. To compute it, the domain is delimited by 34/50°N × 10°W/20°E for the period 1940–2021. Components of HSI are computed using the *thundeR* package (Taszarek, Allen, Brooks, et al., 2021; Taszarek, Allen, Marchio, & Brooks, 2021) with vertical hybrid-sigma ERA5 model levels of pressure, altitude, temperature, dewpoint temperature and wind components. Climatological context of HSI is provided by using a 3-week percentile rank centered around the event. Furthermore, this rank is applied to compute the SST percentiles and anomalies for the same period.

The HSI is also derived from the WRF simulations to analyze the MHW and ACC effects on hail-favorable environments. As with ERA5, HSI is computed with the *thundeR* package. However, here values of the HSI are considered only for grid points with positive values of timestep-maximum Updraft Helicity (Kain et al., 2010) parameter to focus on supercell development (more information in the Text S1 in Supporting Information S1). Ingredients of HSI are also evaluated as those are commonly used in the operational forecasting and climatological studies of significant hail (Allen et al., 2020; Battaglioli et al., 2023; Calvo-Sancho et al., 2022; Nixon et al., 2023; Taszarek, Allen, Groenemeijer, et al., 2020; Taszarek, Allen, Púčik, et al., 2020). These variables entail convective available potential energy (CAPE), 500–800 hPa temperature lapse rate (LR), lifted condensation level height (LCL_HGT), freezing level height (FL_HGT), equilibrium level height (EL_HGT), 0–6 km vertical wind shear (BS_06 km) and the compound convective indices significant hail parameter (SHIP) and supercell composite parameter (SCP). The most-unstable (MU) layer is used to compute parcel thermodynamic parameters. Moreover, the non-parametric Mann-Whitney test (Mann & Whitney, 1947) is used to establish differences (95% confidence) between the WRF-Control and perturbed WRF experiments (WRF-ERA5CLIM and WRF-Preindustrial) for those variables.

3. Synoptic and Mesoscale Environment

A narrow cut-off low over the center-eastern of France evolving into a quasi-omega atmospheric pattern on 30 August 2022, favored the development of a short-wave trough over northeastern Spain (Figure S1 in Supporting Information S1). The supercell storm developed in the Pyrenees due to orographic lift and highly unstable environment (Farnell et al., 2023). The SST and the SST anomaly reach the highest values in comparison to the climatology of a 3-week percentile rank centered on the event day (Figures 1b and 1c). The supercell moved into an environment supportive for severe weather, that is, combination of high CAPE and strong BS06 (Figure 1d). The combination of upper-level large-scale lift, weak CIN, very high CAPE, complex orography conducive to mechanical lifting, strong BS06, and the MHW favored the supercell development and giant hail formation (Nixon et al., 2023; Ricchi, Rotunno, et al., 2023; Ricchi, Sangelantoni, et al., 2023). Further information on the synoptic and mesoscale setup is provided in Supporting Information S1.

4. Climatological Context of the Atmospheric Conditions

The Spanish supercell data set (Figure 2a) indicates that approximately 65% of large hail events feature 5–6 cm hailstones. Giant hail (≥10 cm) occurs in less than 5% of these events. Median and mode hail sizes are 6.00 cm, with an average of 6.15 cm, and the 99th percentile at 10.00 cm. The ESWD (Figure 2b) displays about 40% of events having 5 cm hail. Average, median, and mode hail sizes are lower than the Spanish data set at 5.97, 6.00, and 5.00 cm respectively. The 99th percentile is 10.02 cm. It is important to note that the Spanish data set records maximum hail diameter per supercell, while the ESWD records all hail reports, sometimes multiple for a single supercell.

Both data sets (Figures 2a and 2b) indicate that the Gerona case was an extremely rare event, marking Spain's largest documented hailstone. Púčik et al. (2019) note that giant hail has only been reported 42 times since 2006 in Europe (at the time their paper was published). Giant hail case studies in Europe include 12 cm from Poland (Piasecki et al., 2023), 11 cm from Greece (Papavasileiou et al., 2022) and 14 cm from Italy (Montopoli et al., 2021). In Spain, there were just 4 giant hail observations since 2006, including the Gerona event. Giant hail in Spain is exceptionally rare and typically linked to unique environmental conditions. Yet, recent years have seen a rise in large and giant hail events (Figure S2 in Supporting Information S1).

While observational data sets offer insight into large-hail storms, underreporting in sparsely populated Spanish regions may occur, affecting the data set reliability. To mitigate this, the HSI derived from ERA5 (1940–2021) is utilized, ensuring a stable spatiotemporal climatological context. The HSI 3-week percentile rank (Figure 2c) displays an outstanding environment associated with Gerona's giant hail, with record-breaking values in specific locations of the eastern Mediterranean coast of Spain as well as close to the location of the event.

MU_CAPE and the compound convective indices SHIP and SCP also show record-breaking values on 30 August 2022 in the area, and surroundings, where the giant hail was recorded (Figure S3 in Supporting Information S1). In fact, SHIP values of 2.6 like those developed in the proximity to the giant hail observation (Figure 1d) are rarely observed across Europe (Piasecki et al., 2023; Taszarek, Allen, Groenemeijer, et al., 2020; Taszarek, Allen, Púčik, et al., 2020). Moreover, the MU_EL_HGT value registered on the event is similar to the 99th percentile value from the climatological data. These findings suggest that thermodynamic variables had a great influence on convective storm development, which could be attributed to climate warming that has advanced at an

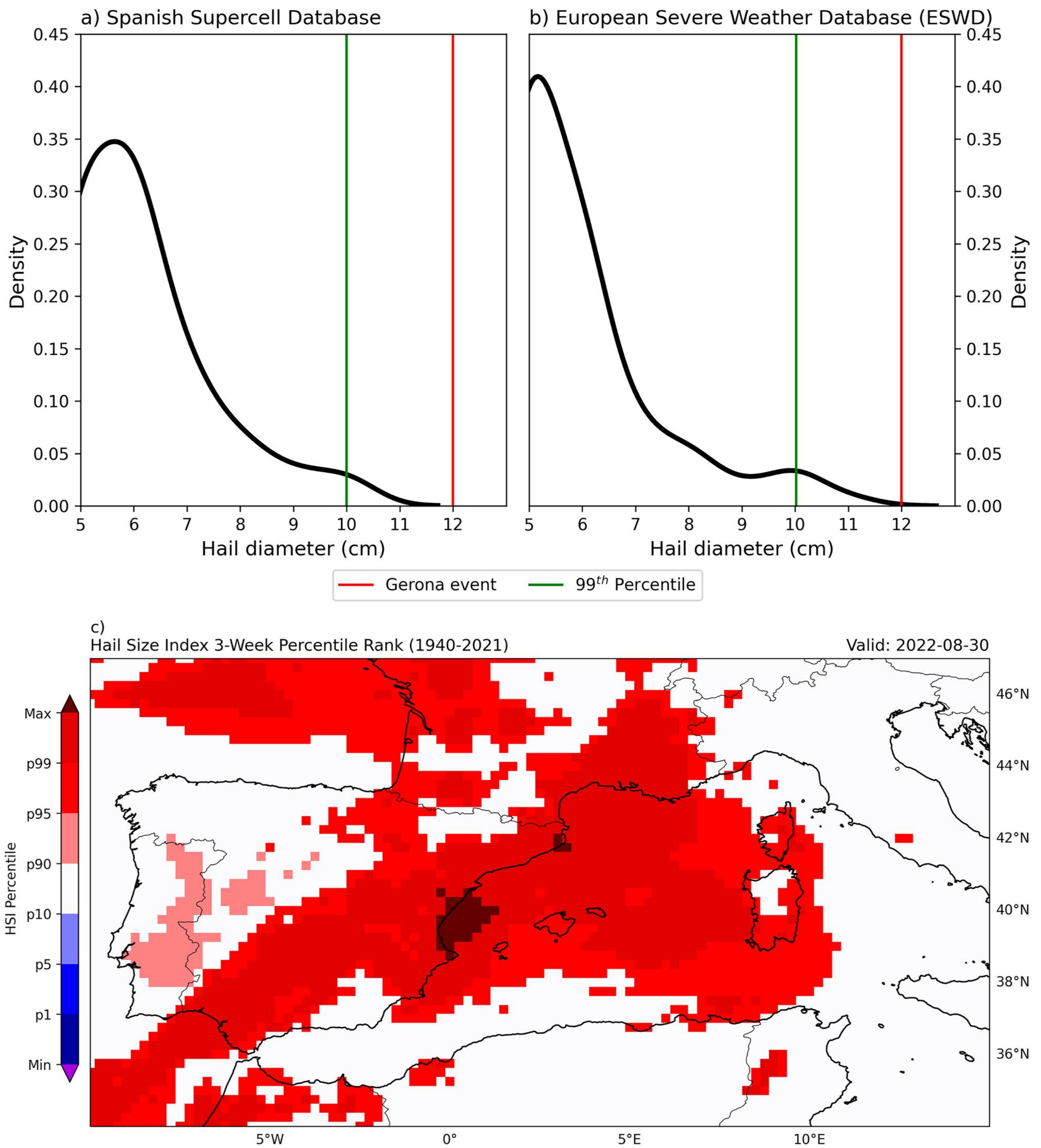

Figure 2. (a) PDF plots of hail reports from the Spanish supercell data set. (b) PDF plots of hail reports from the ESWD. (c) HSI 3-week percentile rank of 30 August 2022, with respect to the period 1940–2021 derived from ERA5 reanalysis.

unprecedented rate in this region over the last decades (Frölicher et al., 2018; Oliver et al., 2018, 2019; Simon et al., 2022). We address this hypothesis in the following section.

5. MHW and ACC Effects on the Giant Hail Event

Long-term patterns of convective environments have revealed an increase in the frequency of severe thunderstorm environments observed in recent decades, which are projected to continue in the future (Calvo-

Sancho, 2021; Lepore et al., 2021; Rädler et al., 2019; Taszarek, Allen, Brooks, et al., 2021; Taszarek, Allen, Marchio, & Brooks, 2021). Thus, the relationship between MHWs and the ACC in the Gerona supercell event needs to be analyzed.

The summer of 2022 presented prolonged and intense heat waves in the Iberian Peninsula. A persistent, record-breaking MHW, lasting 6 weeks with temperatures anomalies averaging +3.27°C, occurred in the Western Mediterranean (Serrano-Notivoli et al., 2023). The SST anomaly in the surroundings of Gerona's littoral coast on 30 August 2022, has been the highest recorded in the period 1940–2021 (Figures 1b and 1c), which enabled surface fluxes to increase the atmospheric moisture content and the convective energy over the area.

Evaluating the results of the MHW effects, the WRF-Control experiment reveals a higher hail size than the WRF-ERA5CLIM experiment (Figure 3a). The difference is significant (p-value <0.01), with higher frequency of low values (<3 cm hail size) in WRF-ERA5CLIM than in WRF-Control. In addition, the WRF-Control experiment shows higher frequencies for large HSI values than the ERA5CLIM experiment. The main effect of the MHW in the convective environment is reflected in the variables related to thermodynamics, such as MU_CAPE, with an important and significant reduction (Figure 3b). The MU_EL_HGT has also a significant reduction for values higher than 13 ,000m in the WRF-ERA5CLIM experiment (Figure 3f), highlighting that the MHW favors deep and intense updrafts (Ricchi, Rotunno, et al., 2023; Ricchi, Sangelantoni, et al., 2023). It should also be noted that the difference in BS_06 km (Figure 3c) is statistically significant (p-value <0.05), revealing that thermodynamic inputs, such as a MHW, could have an influence on large-scale dynamics by reducing the vertical wind shear. Therefore, it can be assumed that the MHW influenced the severity of Gerona's hailstorm.

The annual mean of very large hail hours proxy (HSI ≥5 cm and convective precipitation rate ≥0.25 mm/hr; Figure 4a) reveals higher values in eastern Spain (~4 hr/year) than in the other regions of the country and there are also some points with sporadic hour values favoring large hail. The highest values of large hail hours are located in the region where most supercells and associated large hail develop in Spain, the Maestrazgo, at NE Spain (see Figure 2a in Calvo-Sancho et al., 2022). According to Taszarek, Allen, Marchio, and Brooks (2021), Taszarek, Allen, Brooks, et al. (2021), severe thunderstorm environments in the Iberian Peninsula and its surroundings do not have a significant trend for the period 1979–2019. However, the large hail proxy long-term trend (Figure 4b) displays a significant and positive trend in some areas of eastern Spain. This could be inconsistent with Taszarek, Allen, Marchio, and Brooks (2021) and Taszarek, Allen, Brooks, et al. (2021), but it should be noted that the period 1940–2021 is being used here, and the last three years have had several large hail events in the Iberian Peninsula, especially in 2022 (Figure 4c). These increases are consistent with the observational data sets in Spain (Figure S2 in Supporting Information S1), which might be related to ACC, enhancing moisture and instability, driven by higher SST and air temperatures, promoting steeper lapse rates (Battaglioli et al., 2023).

Finally, the PGWA is applied to assess the ACC effect on Gerona's storm hail size. The WRF-Control and WRF-Preindustrial experiments display similar behaviors in convection initiation and maximum spatial and temporal distribution of reflectivity (not shown). This could indicate that the ACC does not trigger the convective event. However, the WRF-Preindustrial experiment reveals a significant reduction in hail-favorable environment (Figure 3h) in comparison with the WRF-Control, highlighting that the environmental convective conditions in a preindustrial-like climate are less supportive of giant hail (>10 cm) and determine that ACC did boost the environment more prone to develop large hail.

The Updraft Helicity identification method identifies more supercells in WRF-Preindustrial than in WRF-Control. These results demonstrate that a preindustrial-like climate provides conditions favoring the development of supercells with less severity, in terms of hail size, compared to the present climate. While some HSI variables show no significant differences (Figures 3j–3l and 3n), MU_CAPE (Figure 3i) and MU_EL_HGT (Figure 3m) significantly decrease ($p < 0.01$), indicating reduced convective energy and weaker updrafts in a preindustrial-like climate. These results also highlight MU_CAPE and MU_EL_HGT as key factors influencing hail severity. The differences between the preindustrial-like climate and the present one over the hail size of the Gerona event suggest that the current ACC conditions already enhances the convective environment and promotes more extreme events, which has also been found in González-Alemán et al. (2023) for an organized convective event.

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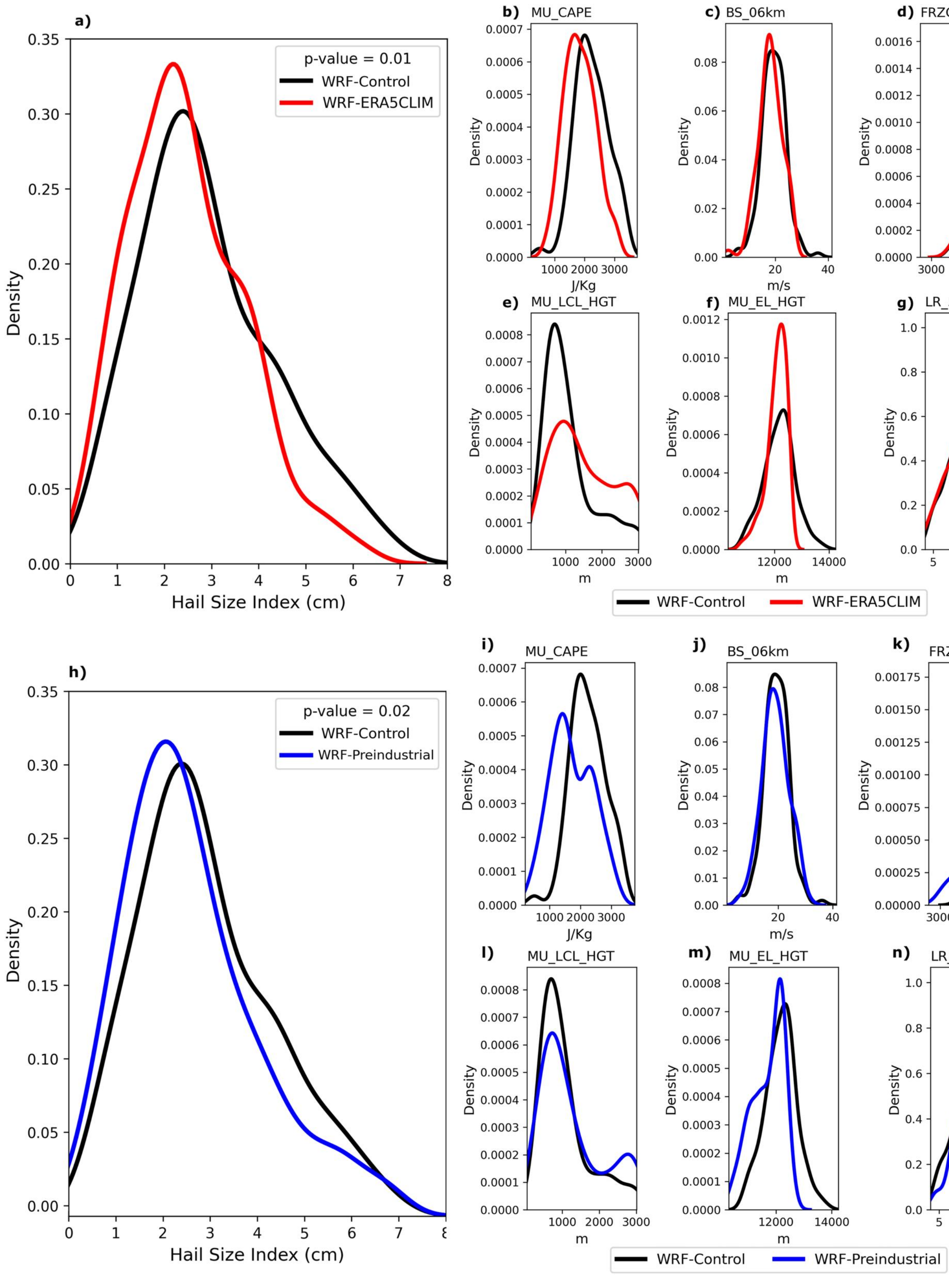

Figure 3. (a) PDF plots of HSI for WRF-Control, WRF-ERA5CLIM (a), and WRF-Preindustrial (h) experiments. From (b) to (g) and (i) to (n) are ingredients of HSI: (b, i) MU_CAPE, (c, j) BS_06km, (d, k) FRZG_HGT, (e, l) MU_LCL_HGT, (f, m) MU_EL_HGT, and (g, n) LR_500800hPa.

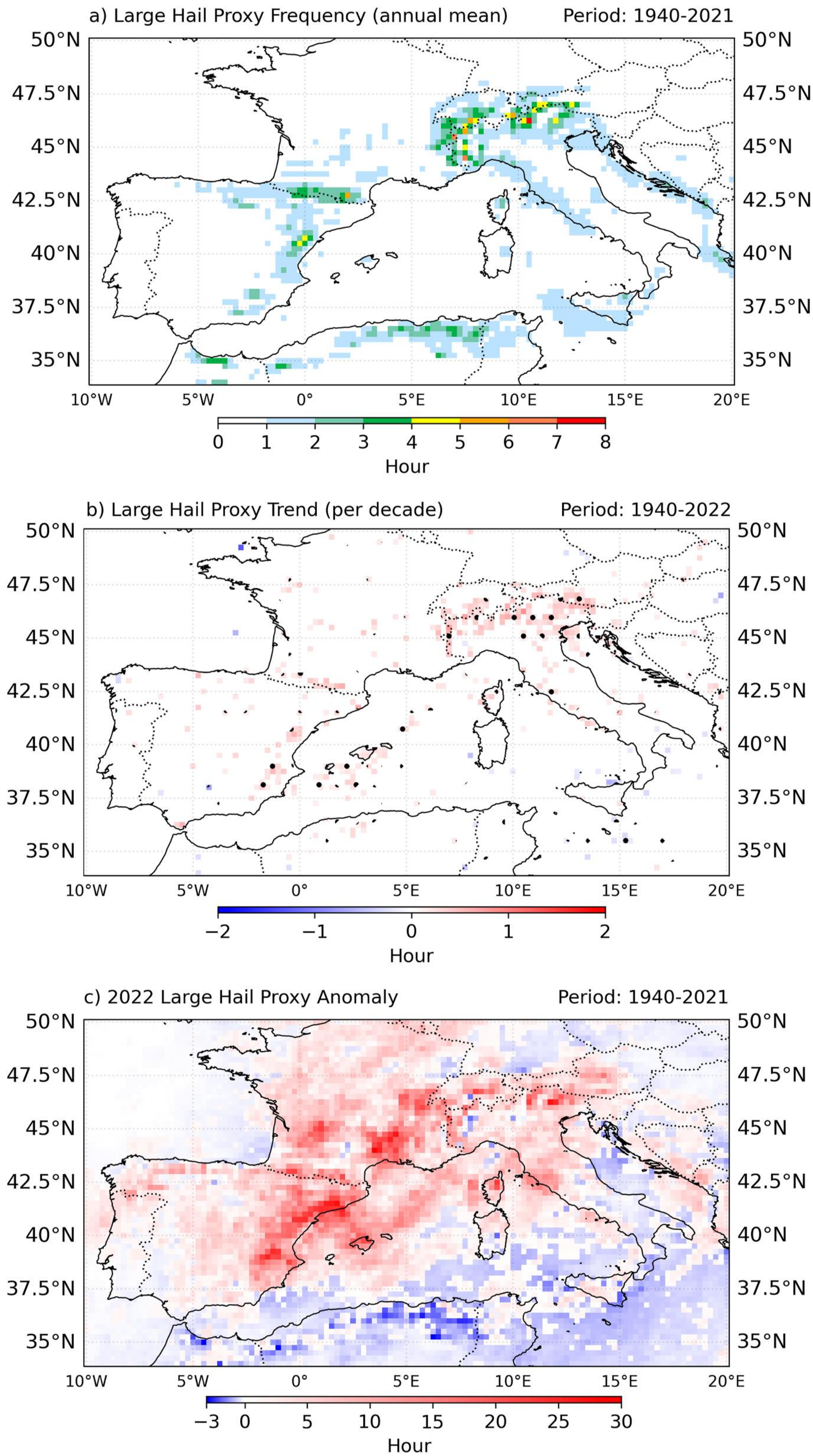

Figure 4. (a) Annual mean number of situations (in hours) with very large hail (HSI >5 cm; Convective Precipitation >0.25 mm) environments. (b) Very large hail proxy long-term trends (1940–2022 period) are derived from annual values and corresponding Sen's slope (values denote change per decade). Black dot denotes a statistically significant trend (p-value <0.05). (c) Anomaly of the large hail proxy in the year 2022 (in hours).

6. Summary and Conclusions

Here we evaluate the main characteristics of the giant-hail storm in northeastern Spain and how a record-breaking MHW and ACC influenced the hail-favorable environment. WRF simulations of the event with 1 km grid resolution were carried out with ERA5 as the initial/boundary conditions. Then, these conditions were perturbed with ERA5 SST climatology and $\overline{\Delta}$ CMIP6 prognostic variables to emulate a preindustrial climate. This is the first study to attribute a giant-hail event to ACC. The authors are not aware of any study addressing how ACC could influence a hailstorm event. The major conclusions are:

- Gerona's giant hail event produced extreme diameter hailstones (12 cm) in Spain, and a record-high considering the 3-week ERA5 percentile rank of HSI parameter, being the largest hailstone ever documented for Spain.
- The supercell that produced giant hail was accompanied by the highest-ever recorded instability in northeastern Spain. The MU_CAPE, MU_EL_HGT, SHIP and SCP, were exceptionally large in the context of convective climatology for northeastern Spain since 1940. Although kinematic variables are equally important as thermodynamic variables for giant hail formation, these findings suggest that thermodynamic variables had a crucial influence on the giant hail event, which is boosted by the highest SST for the period 1940–2022.
- The MHW influenced the hail size growth of the Gerona supercell. The experiments where the MHW is not considered (SST climatology) show a reduction in the HSI, indicating that the MHW substantially affects thermodynamics-related variables on convective environments, which have an important and significant reduction.
- More yearly hours of very large hail environments are found in eastern Spain (∼4 hr per year) with a significant and positive trend in this area. The environmental conditions conducive to very large hail have been reinforced over the region, especially for the last years. These increases might be driven by a warming climate.
- ACC enhanced a convective environment with a record-breaking instability, which favored the giant hail size growth.

The PGWA has allowed us to conclude that in a pre-industrial climate, this event would have likely had a reduced socio-economic impact on Gerona's province as the storm would be less severe. Moreover, deeper research about this event is required to fully grasp the influences of MHWs and ACC in giant-hail storms and how the mesoscale processes affect the giant hail size growth. One of the limitations of the analysis herein presented is the lack of considering the changing aerosol concentration over time and its possible influence on this hail event (Lin et al., 2021). These results are worrying for the Mediterranean region, considering the notable increase in frequency, duration and intensity of MHW events expected in a warming climate (Frölincher et al., 2018; Oliver et al., 2019).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The following GCM data sets used in this study are available through the CMIP6 repository (https://esgf-node.llnl.gov/projects/cmip6/). ERA5 reanalysis is available from the Copernicus Climate Change Service Climate Data Store (https://doi.org/10.24381/cds.bd0915c6, Hersbach et al., 2020). PGWA increments were performed using PGWERA5 v1.1 (Brogli et al., 2023), which can be downloaded from a Github repository (https://github.com/Potopoles/PGW4ERA5.git). Numerical simulations were performed using WRFV4.2, which can be downloaded from the UCAR Github repository (https://github.com/wrf-model/WRF.git). The Spanish Supercell Database is available in Martín and Calvo-Sancho (2023).

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References

Allen, J. T., Giammanco, I. M., Kumjian, M. R., Jurgen Punge, H., Zhang, Q., Groenemeijer, P., et al. (2020). Understanding hail in the Earth system. *Reviews of Geophysics*, *58*(1), e2019RG000665. https://doi.org/10.1029/2019rg000665

Antonescu, B., Schultz, D. M., Holzer, A., & Groenemeijer, P. (2017). Tornadoes in Europe: An underestimated threat. *Bulletin of the American Meteorological Society*, *98*(4), 713–728. https://doi.org/10.1175/bams-d-16-0171.1

Ashley, W. S., Haberlie, A. M., & Gensini, V. A. (2023). The future of supercells in the United States. *Bulletin of the American Meteorological Society*, *104*(1), E1–E21. https://doi.org/10.1175/bams-d-22-0027.1

Battaglioli, F., Groenemeijer, P., Púčik, T., Taszarek, M., Ulbrich, U., & Rust, H. (2023). Modelled multidecadal trends of lightning and (very) large hail in Europe and North America (1950–2021). *Journal of Applied Meteorology and Climatology*, *62*(11), 1627–1653. https://doi.org/10.1175/jamc-d-22-0195.1

Blair, S. F., Laflin, J. M., Cavanaugh, D. E., Sanders, K. J., Currens, S. R., Pullin, J. I., et al. (2017). High-resolution hail observations: Implications for NWS warning operations. *Weather and Forecasting*, *32*(3), 1101–1119. https://doi.org/10.1175/waf-d-16-0203.1

Brimelow, J. C., Burrows, W. R., & Hanesiak, J. M. (2017). The changing hail threat over North America in response to anthropogenic climate change. *Nature Climate Change*, *7*(7), 516–522. https://doi.org/10.1038/nclimate3321

Brogli, R., Heim, C., Mensch, J., Sørland, S. L., & Schär, C. (2023). The pseudo-global-warming (PGW) approach: Methodology, software package PGW4ERA5 v1. 1, validation, and sensitivity analyses [Software]. Geoscientific Model Development, *16*(3), 907–926. https://doi.org/10.5194/gmd-16-907-2023

Brooks, H. E., Lee, J. W., & Craven, J. P. (2003). The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmospheric Research*, *67*, 73–94. https://doi.org/10.1016/s0169-8095(03)00045-0

Calvo-Sancho, C. (2021). *Caracterización de los ambientes convectivos que favorecen el desarrollo de la convección organizada en España: exploración y evolución en el período 1979-2019 mediante reanálisis ERA5* Final Master Thesis. Universidad de Zaragoza. https://doi.org/10.13140/RG.2.2.25129.31841

Calvo-Sancho, C., Díaz-Fernández, J., Martín, Y., Bolgiani, P., Sastre, M., González-Alemán, J. J., et al. (2022). Supercell convective environments in Spain based on ERA5: Hail and non-hail differences. *Weather and Climate Dynamics*, *3*(3), 1021–1036. https://doi.org/10.5194/wcd-3-1021-2022

Czernecki, B., Taszarek, M., Marosz, M., Półrolniczak, M., Kolendowicz, L., Wyszogrodzki, A., & Szturc, J. (2019). Application of machine learning to large hail prediction-The importance of radar reflectivity, lightning occurrence and convective parameters derived from ERA5. *Atmospheric Research*, *227*, 249–262. https://doi.org/10.1016/j.atmosres.2019.05.010

Dahl, J. M. L. (2006). *Supercells—Their dynamics and prediction*. MSc thesis (p. 121). Department of Theoretical Meteorology, Free University of Berlin. Retrieved from http://www.estofex.org/files/dahl_thesis.pdf

Del Genio, A. D., Yao, M. S., & Jonas, J. (2007). Will moist convection be stronger in a warmer climate? *Geophysical Research Letters*, *34*(16). https://doi.org/10.1029/2007gl030525

Dotzek, N., Groenemeijer, P., Feuerstein, B., & Holzer, A. M. (2009). Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmospheric Research*, *93*(1–3), 575–586. https://doi.org/10.1016/j.atmosres.2008.10.020

Farnell, C., Batalla, E., Rigo, T., Pineda, N., Sole, X., Mercader, J., & Martin-Vide, J. (2023). Reanalysis of giant hail event in Catalonia (NE of the Iberian Peninsula). *Atmospheric Research*, *296*, 107051. https://doi.org/10.1016/j.atmosres.2023.107051

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*(7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

González-Alemán, J. J., Insua-Costa, D., Bazile, E., González-Herrero, S., Marcello Miglietta, M., Groenemeijer, P., & Donat, M. G. (2023). Anthropogenic warming had a crucial role in triggering the historic and destructive Mediterranean derecho in summer 2022. *Bulletin of the American Meteorological Society*, *104*(8), E1526–E1532. https://doi.org/10.1175/bams-d-23-0119.1

Herrera-Lormendez, P., John, A., Douville, H., & Matschullat, J. (2023). Projected changes in synoptic circulations over Europe and their implications for summer precipitation: A CMIP6 perspective. *International Journal of Climatology*, *43*(7), 3373–3390. https://doi.org/10.1002/joc.8033

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis [Dataset]. Quarterly Journal of the Royal Meteorological Society, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., et al. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, *141*, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Kain, J. S., Dembek, S. R., Weiss, S. J., Case, J. L., Levit, J. J., & Sobash, R. A. (2010). Extracting unique information from high resolution forecast models: Monitoring selected fields and phenomena every time step. *Weather and Forecasting*, *25*(5), 1536–1542. https://doi.org/10.1175/2010WAF2222430.1

Kawase, H., Watanabe, S., Hirockawa, Y., & Imada, Y. (2022). Timely event attribution of extreme precipitation in Japan: An example of heavy rainfall in July 2020. *Bulletin of the American Meteorological Society*, *103*(3), S118–S123. https://doi.org/10.1175/bams-d-21-0192.1

Kendall, K. (1975). Thin-film peeling-the elastic term. *Journal of Physics D: Applied Physics*, *8*(13), 1449–1452. https://doi.org/10.1088/0022-3727/8/13/005

Kumjian, M. R., & Lombardo, K. (2020). A hail growth trajectory model for exploring the environmental controls on hail size: Model physics and idealized tests. *Journal of the Atmospheric Sciences*, *77*(8), 2765–2791. https://doi.org/10.1175/jas-d-20-0016.1

Kunz, M., Wandel, J., Fluck, E., Baumstark, S., Mohr, S., & Schemm, S. (2020). Ambient conditions prevailing during hail events in central Europe. *Natural Hazards and Earth System Sciences*, *20*(6), 1867–1887. https://doi.org/10.5194/nhess-20-1867-2020

Lau, W. K. M., Shi, J. J., Tao, W. K., & Kim, K. M. (2016). What would happen to Superstorm Sandy under the influence of a substantially warmer Atlantic Ocean? *Geophysical Research Letters*, *43*(2), 802–811. https://doi.org/10.1002/2015gl067050

Lepore, C., Abernathey, R., Henderson, N., Allen, J. T., & Tippett, M. K. (2021). Future global convective environments in CMIP6 models. *Earth's Future*, *9*(12), e2021EF002277. https://doi.org/10.1029/2021ef002277

Lin, Y., Fan, J., Jeong, J. H., Zhang, Y., Homeyer, C. R., & Wang, J. (2021). Urbanization-induced land and aerosol impacts on storm propagation and hail characteristics. *Journal of the Atmospheric Sciences*, *78*(3), 925–947. https://doi.org/10.1175/jas-d-20-0106.1

Ludwig, P., Pinto, J. G., Reyers, M., & Gray, S. L. (2013). The role of anomalous SST and surface fluxes over the southeastern North Atlantic in the explosive development of windstorm Xynthia. *Quarterly Journal of the Royal Meteorological Society*, *140*(682), 1729–1741. https://doi.org/10.1002/qj.2253

Mann, H. B. (1945). Nonparametric tests against trend. Econometrica. *Journal of the Econometric Society*, *13*(3), 245–259. https://doi.org/10.2307/1907187

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, *18*(1), 50–60. https://doi.org/10.1214/aoms/1177730491

Martín, Y., & Calvo-Sancho, C. (2023). Spanish supercell dataset—Hail [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.10257815

Martín, Y., Cívica, M., & Pham, E. (2021). Constructing a supercell database in Spain using publicly available two-dimensional radar images and citizen science. *Annals of the Association of American Geographers*, *111*(5), 1346–1366. https://doi.org/10.1080/24694452.2020.1812371

Meredith, E. P., Semenov, V. A., Maraun, D., Park, W., & Chernokulsky, A. V. (2015). Crucial role of Black Sea warming in amplifying the 2012 Krymsk precipitation extreme. *Nature Geoscience*, *8*, 615–619. https://doi.org/10.1038/ngeo2483

Miglietta, M. M., Mazon, J., Motola, V., & Pasini, A. (2017). Effect of a positive sea surface temperature anomaly on a Mediterranean tornadic supercell. *Scientific Reports*, *7*(1), 12828. https://doi.org/10.1038/s41598-017-13170-0

Montopoli, M., Picciotti, E., Baldini, L., Di Fabio, S., Marzano, F. S., & Vulpiani, G. (2021). Gazing inside a giant-hail-bearing Mediterranean supercell by dual-polarization Doppler weather radar. *Atmospheric Research*, *264*, 105852. https://doi.org/10.1016/j.atmosres.2021.105852

Muramatsu, T., Kato, T., Nakazato, M., Endo, H., & Kitoh, A. (2016). Future change of tornadogenesis-favorable environmental conditions in Japan estimated by a 20-km-mesh atmospheric general circulation model. 気象集誌. 第 2 輯, *94*(0), 105–120. https://doi.org/10.2151/jmsj.2015-053

Nisi, L., Martius, O., Hering, A., Kunz, M., & Germann, U. (2016). Spatial and temporal distribution of hailstorms in the alpine region: A long-term, high resolution, radar-based analysis. *Quarterly Journal of the Royal Meteorological Society*, *142*(697), 1590–1604. https://doi.org/10.1002/qj.2771

Nixon, C. J., Allen, J. T., & Taszarek, M. (2023). Hodographs and Skew T s of hail-producing storms. *Weather and Forecasting*, *38*(11), 2217–2236. https://doi.org/10.1175/waf-d-23-0031.1

Oliver, E. C., Burrows, M. T., Donat, M. G., Sen Gupta, A., Alexander, L. V., Perkins-Kirkpatrick, S. E., et al. (2019). Projected marine heatwaves in the 21st century and the potential for ecological impact. *Frontiers in Marine Science*, *6*, 734. https://doi.org/10.3389/fmars.2019.00734

Oliver, E. C., Perkins-Kirkpatrick, S. E., Holbrook, N., & Bindoff, N. (2018). Anthropogenic and natural influences on record 2016 marine heat waves.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Papavasileiou, G., Kotroni, V., Lagouvardos, K., & Giannaros, T. M. (2022). Observational and numerical study of a giant hailstorm in Attica, Greece, on 4 October 2019. *Atmospheric Research*, *278*, 106341. https://doi.org/10.1016/j.atmosres.2022.106341

Pastor, F., & Khodayar, S. (2023). Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of the Total Environment*, *861*, 160621. https://doi.org/10.1016/j.scitotenv.2022.160621

Pastor, F., Valiente, J. A., & Khodayar, S. (2020). A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote Sensing*, *12*(17), 2687. https://doi.org/10.3390/rs12172687

Patricola, C. M., & Wehner, M. F. (2018). Anthropogenic influences on major tropical cyclone events. *Nature*, *563*(7731), 339–346. https://doi.org/10.1038/s41586-018-0673-2

Peters, J. M., Nowotarski, C. J., & Morrison, H. (2019). The role of vertical wind shear in modulating maximum supercell updraft velocities. *Journal of the Atmospheric Sciences*, *76*(10), 3169–3189. https://doi.org/10.1175/jas-d-19-0096.1

Piasecki, K., Matczak, P., Taszarek, M., Czernecki, B., Skop, F., & Sobisiak, A. (2023). Giant hail in Poland produced by a supercell merger in extreme instability–A sign of a warming climate? *Atmospheric Research*, *292*, 106843. https://doi.org/10.1016/j.atmosres.2023.106843

Poręba, S., Taszarek, M., & Ustrnul, Z. (2022). Diurnal and seasonal variability of ERA5 convective parameters in relation to lightning flash rates in Poland. *Weather and Forecasting*, *37*(8), 1447–1470. https://doi.org/10.1175/waf-d-21-0099.1

Pucik, T. (2022). On the predictability of the giant hail event in Catalonia. Retrieved from https://www.essl.org/cms/on-the-predictability-of-the-giant-hail-event-in-catalonia/

Púčik, T., Castellano, C., Groenemeijer, P., Kühne, T., Rädler, A. T., Antonescu, B., & Faust, E. (2019). Large hail incidence and its economic and societal impacts across Europe. *Monthly Weather Review*, *147*(11), 3901–3916. https://doi.org/10.1175/mwr-d-19-0204.1

Rädler, A. T., Groenemeijer, P. H., Faust, E., Sausen, R., & Púčik, T. (2019). Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. *npj Climate and Atmospheric Science*, *2*(1), 30. https://doi.org/10.1038/s41612-019-0083-7

Raupach, T. H., Martius, O., Allen, J. T., Kunz, M., Lasher-Trapp, S., Mohr, S., et al. (2021). The effects of climate change on hailstorms. *Nature Reviews Earth & Environment*, *2*(3), 213–226. https://doi.org/10.1038/s43017-020-00133-9

Reed, K. A., Stansfield, A. M., Wehner, M. F., & Zarzycki, C. M. (2020). Forecasted attribution of the human influence on Hurricane Florence. *Science Advances*, *6*(1), eaaw9253. https://doi.org/10.1126/sciadv.aaw9253

Reed, K. A., Wehner, M. F., Stansfield, A. M., & Zarzycki, C. M. (2021). Anthropogenic influence on hurricane Dorian's extreme rainfall. *Bulletin of the American Meteorological Society*, *102*(1), S9–S15. https://doi.org/10.1175/bams-d-20-0160.1

Ricchi, A., Rotunno, R., Miglietta, M. M., Picciotti, E., Montopoli, M., Marzano, F. S., et al. (2023). Analysis of the development mechanisms of a large-hail storm event on the Adriatic Sea. *Atmospheric Research*, *296*, 107079. https://doi.org/10.1016/j.atmosres.2023.107079

Ricchi, A., Sangelantoni, L., Redaelli, G., Mazzarella, V., Montopoli, M., Miglietta, M. M., et al. (2023). Impact of the SST and topography on the development of a large-hail storm event, on the Adriatic Sea. *Atmospheric Research*, *296*, 107078. https://doi.org/10.1016/j.atmosres.2023.107078

Sato, T., Kimura, F., & Kitoh, A. (2007). Projection of global warming onto regional precipitation over Mongolia using a regional climate model. *Journal of Hydrology*, *333*(1), 144–154. https://doi.org/10.1016/j.jhydrol.2006.07.023

Schär, C., Frei, C., Lüthi, D., & Davies, H. C. (1996). Surrogate climate-change scenarios for regional climate models. *Geophysical Research Letters*, *23*(6), 669–672. https://doi.org/10.1029/96gl00265

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.2307/2285891

Serrano-Notivoli, R., Tejedor, E., Sarricolea, P., Meseguer-Ruiz, O., de Luis, M., Saz, M. Á., et al. (2023). Unprecedented warmth: A look at Spain's exceptional summer of 2022. *Atmospheric Research*, *293*, 106931. https://doi.org/10.1016/j.atmosres.2023.106931

Simon, A., Plecha, S. M., Russo, A., Teles-Machado, A., Donat, M. G., Auger, P. A., & Trigo, R. M. (2022). Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. *Frontiers in Marine Science*, *9*, 892201. https://doi.org/10.3389/fmars.2022.892201

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., et al. (2019). A description of the advanced research WRF version 4 (p. 145). NCAR tech. note ncar/tn-556+ str.

Taszarek, M., Allen, J. T., Brooks, H. E., Pilguj, N., & Czernecki, B. (2021). Differing trends in United States and European severe thunderstorm environments in a warming climate. *Bulletin of the American Meteorological Society*, *102*(2), E296–E322. https://doi.org/10.1175/bams-d-20-0004.1

Taszarek, M., Allen, J. T., Groenemeijer, P., Edwards, R., Brooks, H. E., Chmielewski, V., & Enno, S. E. (2020). Severe convective storms across Europe and the United States. Part I: Climatology of lightning, large hail, severe wind, and tornadoes. *Journal of Climate*, *33*(23), 10239–-10261. https://doi.org/10.1175/jcli-d-20-0345.1

Taszarek, M., Allen, J. T., Marchio, M., & Brooks, H. E. (2021). Global climatology and trends in convective environments from ERA5 and rawinsonde data. *NPJ climate and atmospheric science*, *4*(1), 35. https://doi.org/10.1038/s41612-021-00190-x

Taszarek, M., Allen, J. T., Púčik, T., Hoogewind, K. A., & Brooks, H. E. (2020). Severe convective storms across Europe and the United States. Part II: ERA5 environments associated with lightning, large hail, severe wind, and tornadoes. *Journal of Climate*, *33*(23), 10263–10286. https://doi.org/10.1175/jcli-d-20-0346.1

Trapp, R. J., Diffenbaugh, N. S., Brooks, H. E., Baldwin, M. E., Robinson, E. D., & Pal, J. S. (2007). Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences*, *104*(50), 19719–19723. https://doi.org/10.1073/pnas.0705494104

Trapp, R. J., Diffenbaugh, N. S., & Gluhovsky, A. (2009). Transient response of severe thunderstorm forcing to elevated greenhouse gas concentrations. *Geophysical Research Letters*, *36*(1). https://doi.org/10.1029/2008gl036203