Anthropogenic Warming Had a Crucial Role in Triggering the Historic and Destructive Mediterranean Derecho in Summer 2022

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A record-breaking marine heatwave and anthropogenic climate change have substantially contributed to the development of an extremely anomalous and vigorous convective windstorm in August 2022 over the Mediterranean Sea.

On 17 August 2022, very high atmospheric instability and strong wind shear developed over the western Mediterranean. Ahead of an eastward moving shortwave trough, convective cells organized into a bow-shaped system, producing a long swath of severe winds from the Balearic Islands to southern Czech Republic on August 18 (Fig. 1a), with maximum wind gust of 62.2 m s^{-1}, measured by Météo France at Marignana, Corsica. In total, 12 people died and 106 people were injured. This system can easily be classified as a derecho (ESSL 2022), a particularly long-lived and severe convective windstorm (Johns and Hirt, 1987; Corfidi et al, 2016). Concurrent with the derecho, a record-breaking marine heatwave (MHW) was present over the Mediterranean Sea during summer 2022, peaking in July. The sea surface temperature (SST) anomalies exceeded 3°C (see Fig. 1b) over the region where the storm developed.

Derechos have been reported in different parts of Europe (e.g., Gatzen 2004; Punkka et al. 2006; Gatzen

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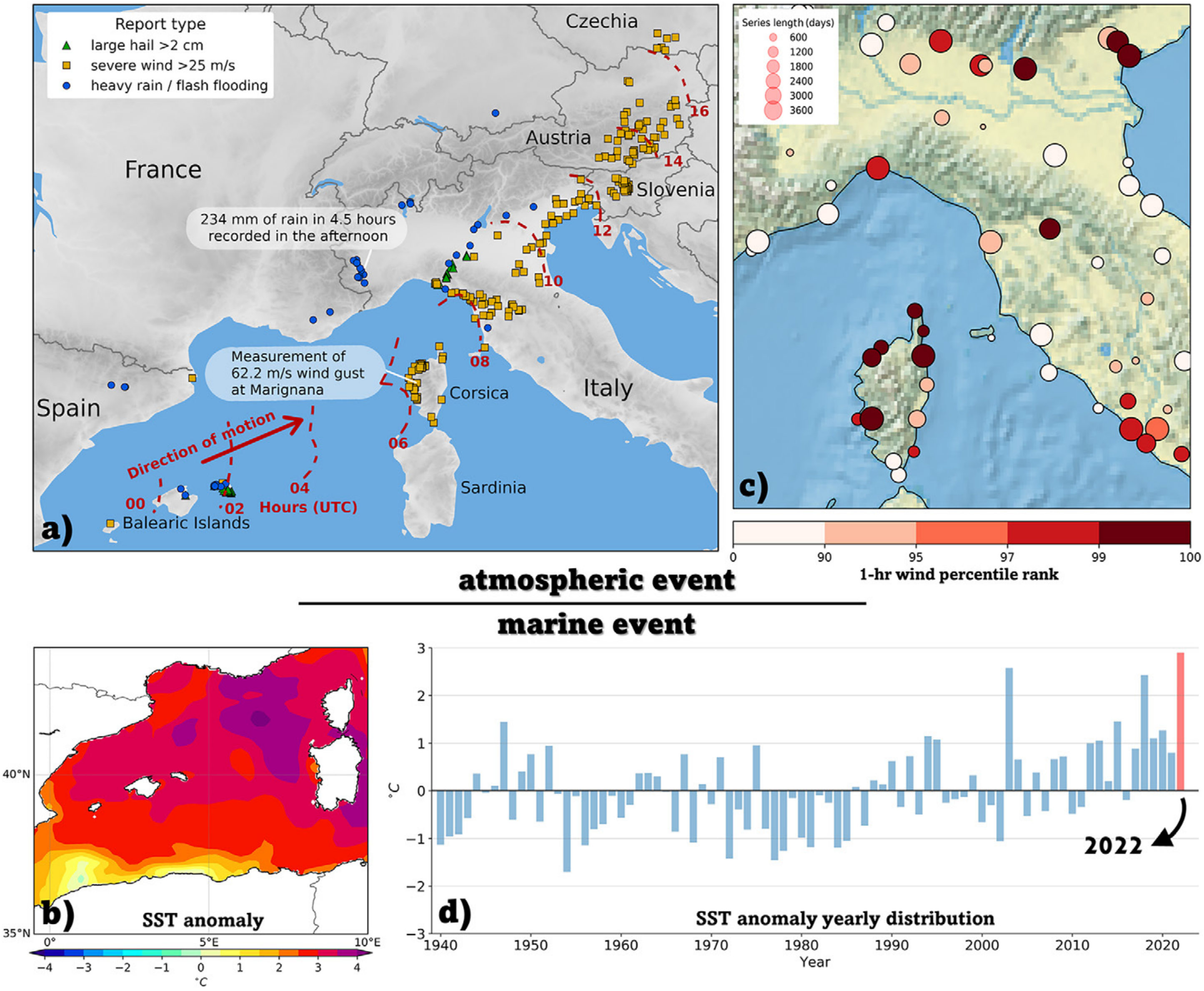


Fig. 1. (a) Visual description of the atmospheric event: Severe weather reports on 18 August 2022 between 0000 and 1800 UTC from the European Severe Weather Database (Dotzek et al. 2009) with indicated isochrones (based on the times of the reports; dashed red lines) of the leading edge of the bow echo. (b) Western Mediterranean SST anomaly with respect to the period 1940–2022 averaged over 1–17 Aug (period preceding the event), derived from ERA5 reanalysis (Hersbach et al. 2020). (c) Percentile of daily maximum mean 1-h wind recorded on 17 Aug with respect to the climatology in July–September from the global hourly Integrated Surface Database (ISD; Smith et al. 2011). (d) As in (b), but for the time series of SST anomalies averaged over the area and period in (b).

et al. 2020; Chernokulsky et al. 2022) but in the Mediterranean regions they are rare. One major derecho, however, occurred in Catalonia and southern France in summer 2003, with gusts up to 52 m s^{-1} (López 2007). Given the rareness of this kind of convective storms over the region and the simultaneous presence and the severity of the MHW, a question that arises is to what extent the convective event was driven or amplified by the MHW and, ultimately, by anthropogenic climate change (ACC) (several studies have documented a link between ACC-driven environmental changes and the characteristics of convective storms; Trapp et al. 2007; Púčik et al. 2017; Miglietta et al. 2017; Rädler et al. 2019; Ashley et al. 2023).

Typical risk-based methodologies for extreme event attribution to ACC (like those used in large-scale phenomena, e.g., record-breaking heatwaves, where different climate model simulations are directly compared; e.g., Otto et al. 2012) cannot be applied to local severe convective storms since these are not well resolved by current climate models. However, a solution for attributing small-scale events is to use models that explicitly simulate the storms. Here we follow two approximations to analyze the derecho event and its relationship with the MHW and ACC. First, we study the sensitivity to the SST and then we perform pseudo-global warming (PGW) simulations (Schär et al. 1996). This last approach, which is part of the storyline attribution methods (Shepherd et al. 2018), also referred to as forecast-based attribution (Leach et al. 2021), has been recently applied to extreme events such as hurricanes (e.g., Patricola and Wehner 2018; Reed et al. 2020, 2021) and heavy rainfall (Kawase et al. 2022), but we are not aware of studies applying it to individual convective storms.

Methods

AROME model simulations. We assessed the influence of the exceptionally warm SSTs (related to the MHW) on the derecho event, using the Météo-France nonhydrostatic operational model AROME (Seity et al. 2011) at 1.3 km grid spacing and with hourly full 3DVar assimilation. Three sensitivity experiments were performed by re-running with a uniform SST perturbation (−3°, −2° and −1°C). By using a full 3DVar system we expect less spinup in the boundary layer compared to a simple cooling of the SST and a more realistic adaptation of the model to the new SST conditions. All the experiments run every 3 h, from 14 until 17 August at 2100 UTC. This model was chosen for these experiments because it correctly simulated the extreme intensity of the derecho wind gusts and permitted us to use a 3DVar analysis.

The pseudo-global warming and forecast-based attribution approaches. To analyze the impact of ACC on the derecho event, we used the Model for Prediction Across Scales (MPAS; Skamarock et al. 2012) initially forced with initial conditions from the Global Forecast System (NCEP-GFS) analysis at 0000 UTC on 17 August (factual run). We then repeated the simulations by perturbing only the NCEP-GFS initial conditions (as MPAS is a global model) with the anthropogenic signals extracted from five different CMIP6 climate models (O'Neill et al. 2016; see Table 1). All the purely thermodynamic variables associated with the event (skin temperature, SST, and the air temperature and specific humidity), as well as greenhouse gases, were perturbed to reflect preindustrial and future conditions (counterfactual runs). More information on the experiments is provided in the supplemental text.

Results

Observed analyses. Robust conclusions about the extreme nature of the convective storm itself are hard to draw. Even though European forecasters (ESSL 2022) and informal analysis point towards an extremely rare convective event for Europe, even similar to top intensity U.S. derechos, no robust data analysis can be provided in this regard because of its intrinsic nature and its development over the sea, where measurements are scarce. However, its extreme nature may be inferred from a fixed regional location affected by it. In fact, in weather stations of Corsica, mainly those located in the northwestern side (the first land region impacted by the derecho), registered wind speeds were exceptional compared to the local climatology (Fig. 1c), breaking monthly and even annual records in several locations (Table ES1). Some of these records were doubled.

The extremeness of the summer 2022 MHW is evidenced by the high SST anomalies (ERA5 reanalysis; Hersbach et al. 2020) in the first half of August 2022 (Fig. 1d), which ranks first among all years since 1960. The record-breaking conditions of this MHW are associated with a changing SST distribution over the region, with higher mean but also broader distribution in the period 1993–2022 with respect to 1940–69 (Fig. ES2). This broader distribution causes the 95th percentile to increase by 1.5 °C in comparison to 0.8 °C of the mean. While we did not analyze the specific drivers for this event, its occurrence is consistent with the MHW increase in frequency, duration, and intensity in observational data (Oliver et al. 2018; Simon et al. 2022) and with anthropogenic forcing and a warming climate in climate model simulations (Frölicher et al. 2018; Oliver et al. 2019).

Model simulations. Given the expected changes in MHWs, an evaluation of the relationship between the derecho and the SSTs is first undertaken. The results of the sensitivity experiments with AROME (Figs. 2a,b) shows that the convective event is highly sensitive to SST, being more

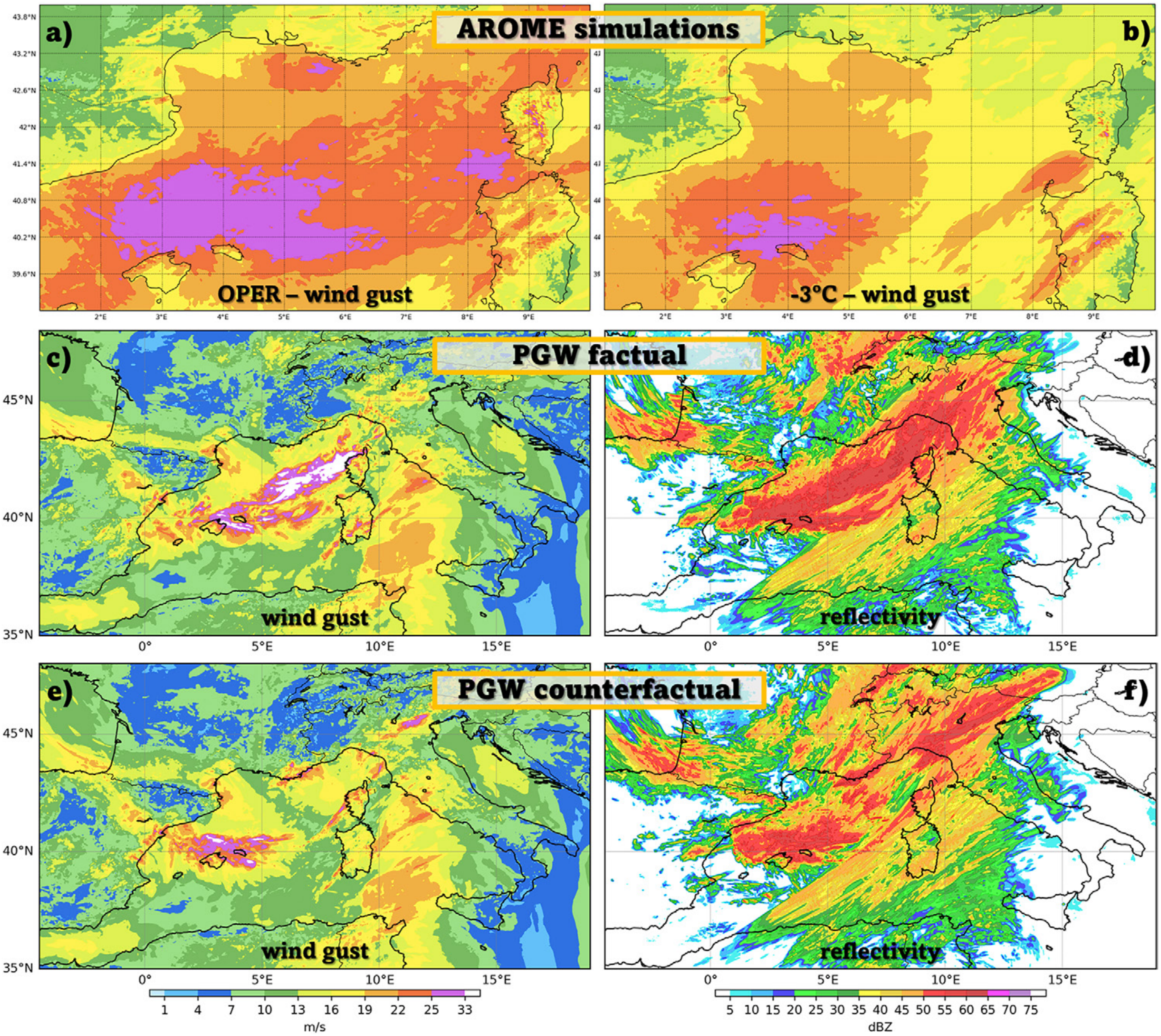


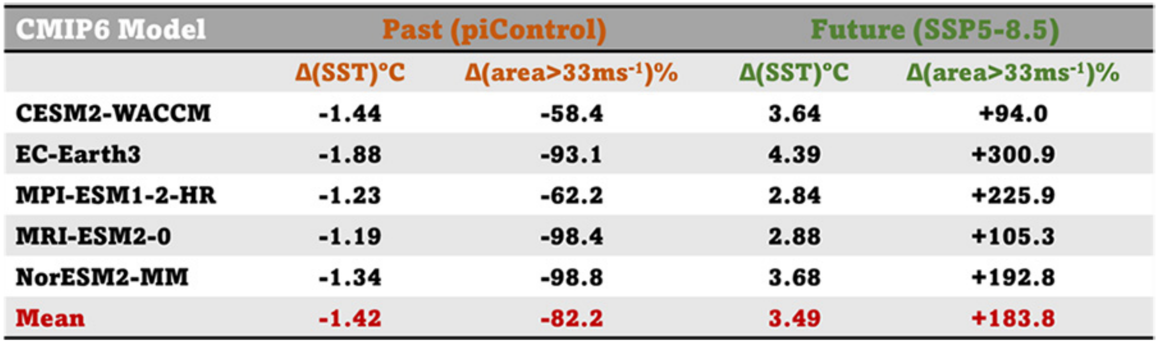
Fig. 2. Ensemble mean of maximum wind gusts (m s^{-1}) of the simulations initialized at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC for (a) the AROME operational (OPER) simulations and (b) perturbing SSTs by −3°C. (c) Maximum wind gusts (m s^{-1}) and (d) maximum reflectivity (dB*Z*) from 2100 UTC 17 Aug to 1200 UTC 18 Aug 2022 in the MPAS-PGW simulation for the factual world. (e),(f) As in (c),(d), respectively, but for counterfactual past (piControl) world simulation perturbed with the EC-Earth3 CMIP6 model.

organized, longer-lasting, and more intense (within the mesoscale predictability limits) in the operational runs than 3 °C cooler SST, corresponding to the MHW SST anomaly. Strong convective wind gusts with a longer swath from the north of the Balearic Islands to Corsica and northern Italy can be observed. An inspection of the –2 ° and –1 °C sensitivity experiments (not shown) indicates that the influence of SSTs on the convective activity remains similar at –2°C but it is strongly reduced at –1°C.

However, the SST anomaly associated with the MHW may not be completely caused by actual ACC conditions. To provide a better estimate of the ACC contribution to the convective event, PGW simulation outputs (EC-Earth3 forcing) are shown in Figs. 2c–f. They clearly indicate that the wind gusts and maximum reflectivity are both sensitive to the initial conditions. The factual simulation (Fig. 2c,d) is able to reproduce the development of a convective windstorm compatible with a derecho, although with a stronger meridional component and weaker intensity (~40–50 $\mathrm{m\ s^{-1}}$) than observed. Further details on the model evaluation are provided in the supplemental text and Fig. ES1.

Conversely, in the counterfactual past simulation (Fig. 2e,f), no strong and organized convective system develops over the region. Instead, convection decays north of the Balearic Islands, where the storm precursor of the derecho developed in the real scenario. Thus, environmental conditions resembling preindustrial climate do not support the development of a derecho. Also, the initial development of the convective precursor in the counterfactual simulation (as in reality) minimizes the possibility of having created overly artificial atmospheric states (e.g., with strongly enhanced convective inhibition) when the environment is perturbed. This supports the idea of ACC having a specific role in the organization of the convective storms.

Figure 2 illustrates the results based on the simulations perturbed with the forcing from the EC-Earth3 model, but such single-model estimates are affected by uncertainties related to internal climate variability and model choice. We therefore also performed these experiments with the forcing estimates derived from five different CMIP6 models (Table 1), where a similar behavior is obtained. However, we consider the average of these different realizations (last row) as our best estimate of an anthropogenic signal, still showing a drastic weakening of the convective activity in the absence of anthropogenic warming.



CMIP6 Model	Past (piControl)		Future (SSP5-8.5)	
	Δ(SST)°C	Δ(area>33ms^{-1})%	Δ(SST)°C	Δ(area>33ms^{-1})%
CESM2-WACCM	-1.44	-58.4	3.64	+94.0
EC-Earth3	-1.88	-93.1	4.39	+300.9
MPI-ESM1-2-HR	-1.23	-62.2	2.84	+225.9
MRI-ESM2-0	-1.19	-98.4	2.88	+105.3
NorESM2-MM	-1.34	-98.8	3.68	+192.8
Mean	-1.42	-82.2	3.49	+183.8

Table 1. More information on the pseudo-global warming simulations performed, extended to all the CMIP6 models used in this study. The first column indicates the changes in SST between the factual and counterfactual [past (piControl)] runs over the same region as in Fig. 1b. The second column indicates the same as the first column but for changes in the area with wind speed above 33 $\mathrm{m\ s^{-1}}$. The third and fourth columns indicate the same as the first and second columns, but for future (SSP5–8.5) runs. The last row indicates the mean for all the simulations.

The effect of the ACC background signal on the development of the observed derecho is further supported by the counterfactual future simulation (Fig. ES2). A world with a strong

ACC scenario (SSP5–8.5) not only fosters the development of an extreme derecho, but also provides environmental conditions supporting a larger (up to +300%, Table 1) convective system with even higher intensity (up to +47%; not shown) in terms of maximum wind gust. This suggests that warm-season convective events over the Mediterranean Sea may become more extreme under continued global warming in the future.

Conclusions

Convection-permitting simulations with different SST anomalies indicate that the rare and severe convective windstorm developed over the western Mediterranean Sea in August 2022 was substantially amplified by the extreme marine heatwave. Pseudo-global warming simulations showed that these conditions over the region, associated with current anthropogenic climate change forcing, contributed to the triggering of the derecho by making environmental factors more favorable for convective amplification. Focusing only on the thermodynamic contribution from global warming, this study shows that, in case a similar dynamical synoptic situation had happened in a preindustrial climate, only ordinary convective cells would have formed, without the development of the derecho. The processes by which sea surface temperature anomalies strongly influence the system warrant further study, especially since experiments suggest that continued warming may even lead to larger and stronger derechos in the future. This is a worrying result for the region as marine heatwaves are increasing in frequency, duration, and intensity.

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