Will today's proxies work tomorrow? Revisiting the stationarity assumption for severe convective environments

Iris Thurnherr[1,*], Monika Feldmann[2], Killian Brennan[2], Sandro Beer[2], Lena Wilhelm[2], Ruoyi Cui[3], Michael Sprenger[1], Olivia Romppainen-Martius[2] and Heini Wernli[1]

[1]ETH Zurich, [2]University of Bern, [3]Agroscope Switzerland *iris.thurnherr@env.ethz.ch

1 Introduction

Many severe storm climatologies are based on environmental proxies and statistical/ML models that link atmospheric conditions to storm occurrence. These approaches form the basis for many long-term trend analyses, yet they all assume that the relationship between environments and severe weather remains stationary over time. In a warming climate, both environments and their interdependencies may change, challenging this assumption.

Using tracking of hail cells and supercell storms in convection-permitting climate simulations, we can directly test whether today's proxies will still work tomorrow.

2 COSMO climate simulations and tracking

11-year present-day and future climate simulations using COSMO 6.0 [5,6]

- 2.2 km grid spacing
- 1-moment graupel schemes with online HAILCAST [7] hail diagnostic providing 5-min maximum hail diameter
- Present day: 2011-2021, driven by ERA5 reanalysis
- Future: 2011-2021 + 3°C global warming using PGW approach[8]
- Setup tested and explored in previous case-study and seasonal simulations[9,10]

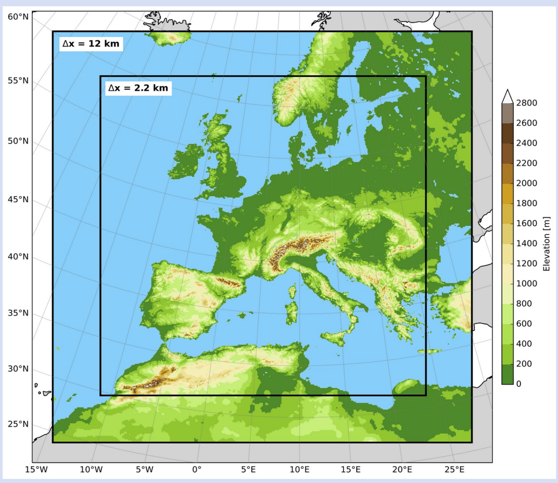


Figure 1 Model topography and domains with ocean/sea indicated in blue. The full outer domain with 12 km grid spacing is shown, with the bold black box indicating the inner domain with 2.2 km grid spacing.

Storm tracking and inflow definition

- Hail storm tracking uses 5min output of maximum hail size[12] to identify storm track.
- Supercell tracking uses 5min output fields of surface precipitation and hourly updraft and vertical velocity[13].
- Along each storm track, circles of 60km radius were extracted around storm center.

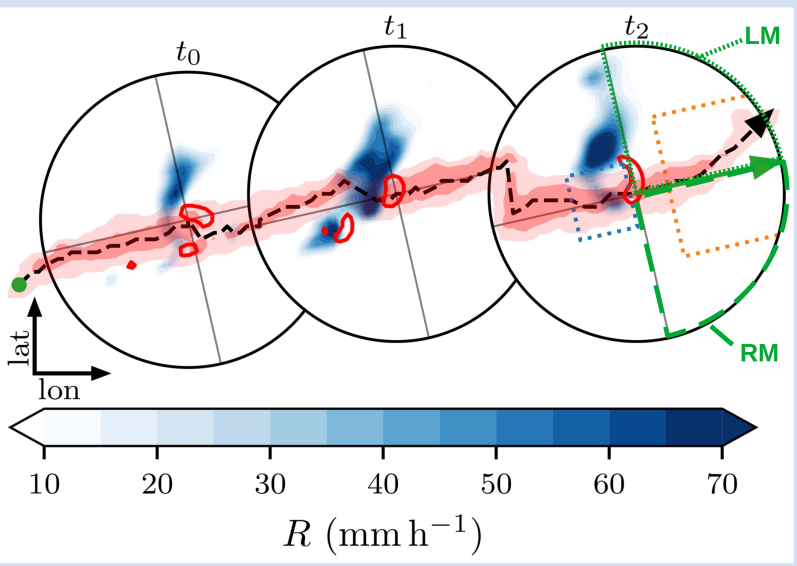
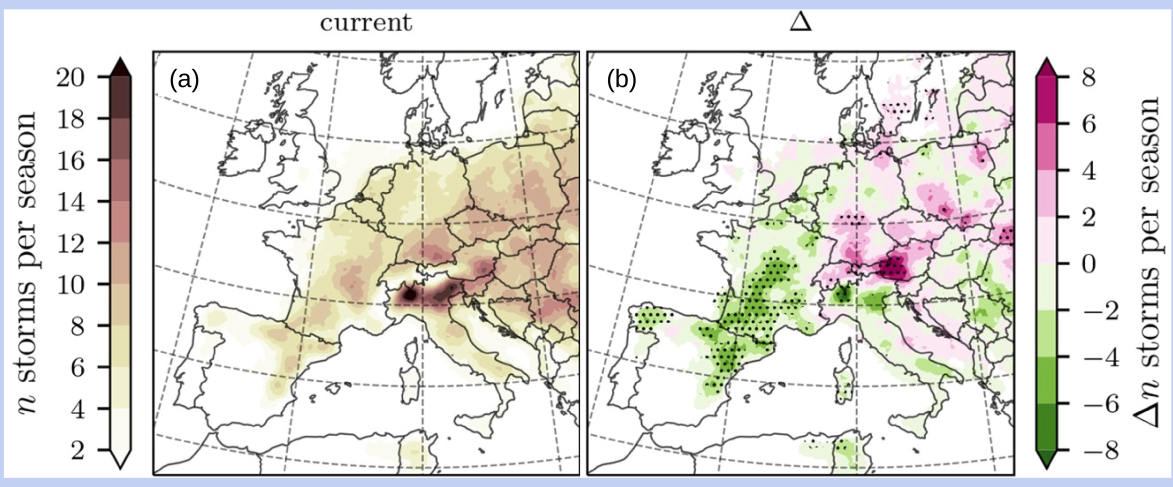


Figure 2 Schematic view of three footprints (black circles) extracted along an example storm track at intervals of 1 h. Blue shading shows the 5 min rain rate, red contours indicate 10 m s−1 updraft at 400 hPa, and the black dashed line and arrow reveal the storm track and direction of movement, respectively. The orange dotted line indicates the extent of the inflow sector of the hail storm, which is a 50×50 km2 box, 10 km ahead of the storm center, the green dashed lines the inflow sector of the supercell storms (LM: for left movers; RM: for right movers). From Brennan et al. (2025).

3 Hail climatology

Figure 2 (a) Number of tracked hail storms per season with lifetimes ≥1 h in summer in the (a) current climate. (b) shows the difference between future and current climate simulations (filled contours); dots indicate regions where the difference is significant (>2σ according to n=1000 bootstrap samples). Figure from Brennan et al. (2025).



Climatology

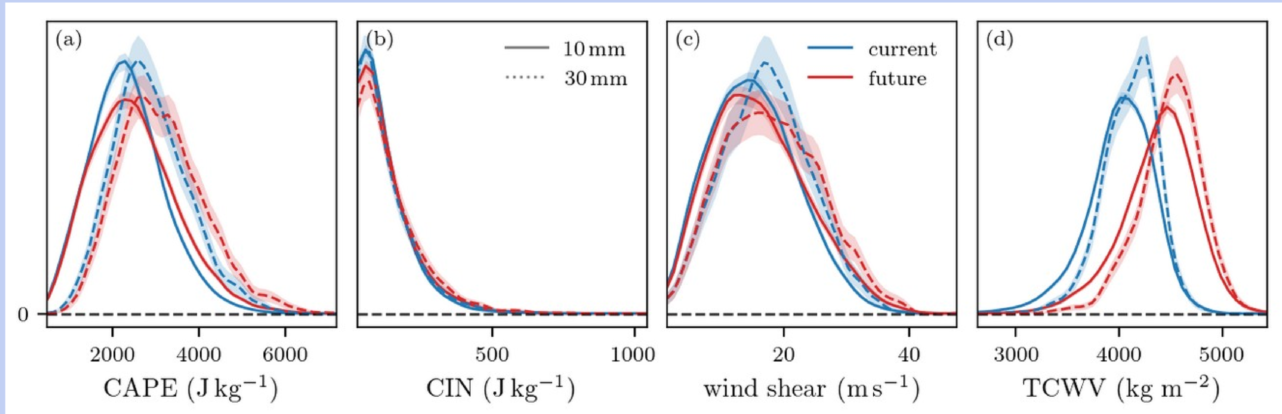
Hail hot spot in Po valley, eastern Spain and middle-eastern Europe.

Climate change signal

Hail storms decrease in southwestern Europe, and increase over and to the north of the Alps, northeastern Europe and eastern Mediterranean.

4 Hail proxy stationarity

Figure 8 Probability density functions of inflow (a-c) and storm (d) environments for hail cells (see Brennan et al. 2024) with a hail diameter above 10mm (solid) and 30mm (dashed) for the CTRL (blue) and PGW (red) simulation.



Comparison of pre-hail storm environments now and with +3°C global warming level

- Small increase in CAPE, CIN and wind shear with global warming
- Increase in freezing level height for larger hail stones and in PGW simulation
- The increase in CAPE and wind shear in the inflow depends on the hail size of the hail storm
- CIN and HZERO show only week dependence on hail stone size

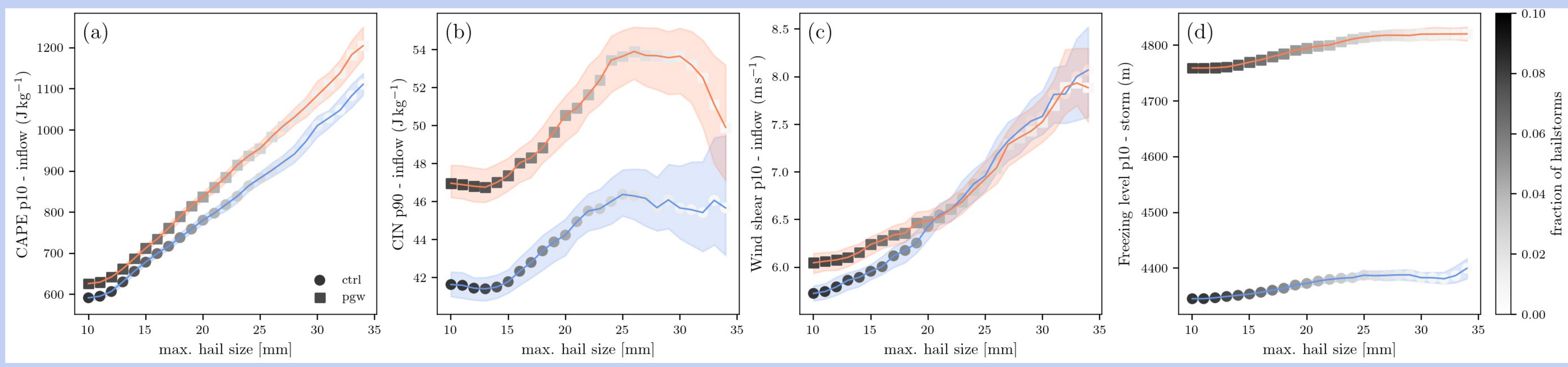
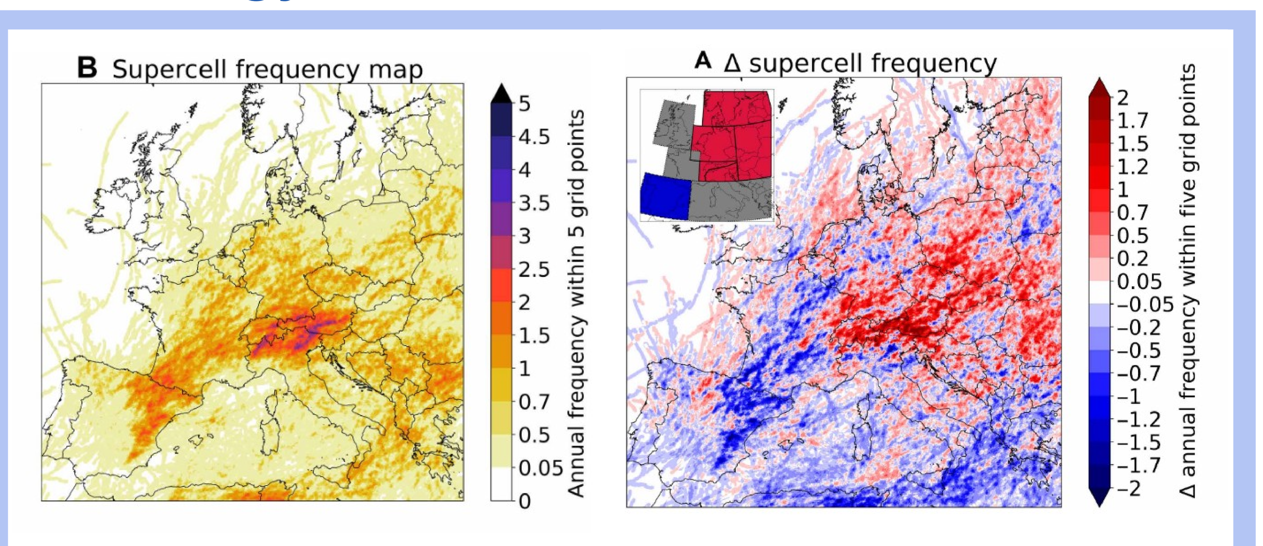


Figure 8 Conditions of inflow (a-c) and storm (d) environments for different maximum hail sizes in hail cells for the CTRL (blue) and PGW (red) simulation: (a) 10th percentile of most unstable CAPE, (b) 90th percentile of most unstable CIN, (c) 10th percentile of vertical wind shear and (d) 10th percentile of freezing level. The dots are coloured by the fraction of hail storm in each hail size bin. The shading denotes the 5th to 95th percentile range of n=1000 bootstrapped samples.

5 Supercell climatology

Figure 2 (A) Annual average supercell track frequency in present climate, within five grid points (B) Annual average difference in supercell track frequency [future – present]; inset shows regionally aggregated significant changes in track number. Red, significant positive; blue, significant negative; gray, no significant change. Figure from Feldmann et al. (2025).



Climatology

Supercell hot spots similar to hail hot spots, surrounding mountain ranges.

Supercells can cross the mountain barrier → no absolute minimum over the Alps.

Climate change signal

Supercell tracks show similar trends in occurrence frequency with a shift toward northeastern Europe and higher altitudes.

6 Supercell proxy stationarity

Comparing pre-supercell environments now and with +3°C global warming

- The lower bound of several environmental metrics, such as CAPE, shear and CIN does not change markedly
- Latitudinal dependence of CIN and CAPE in inflow region
- Larger mean max. hail size in supercells than in hail cells
- Small variations in vertical wind shear with CAPE

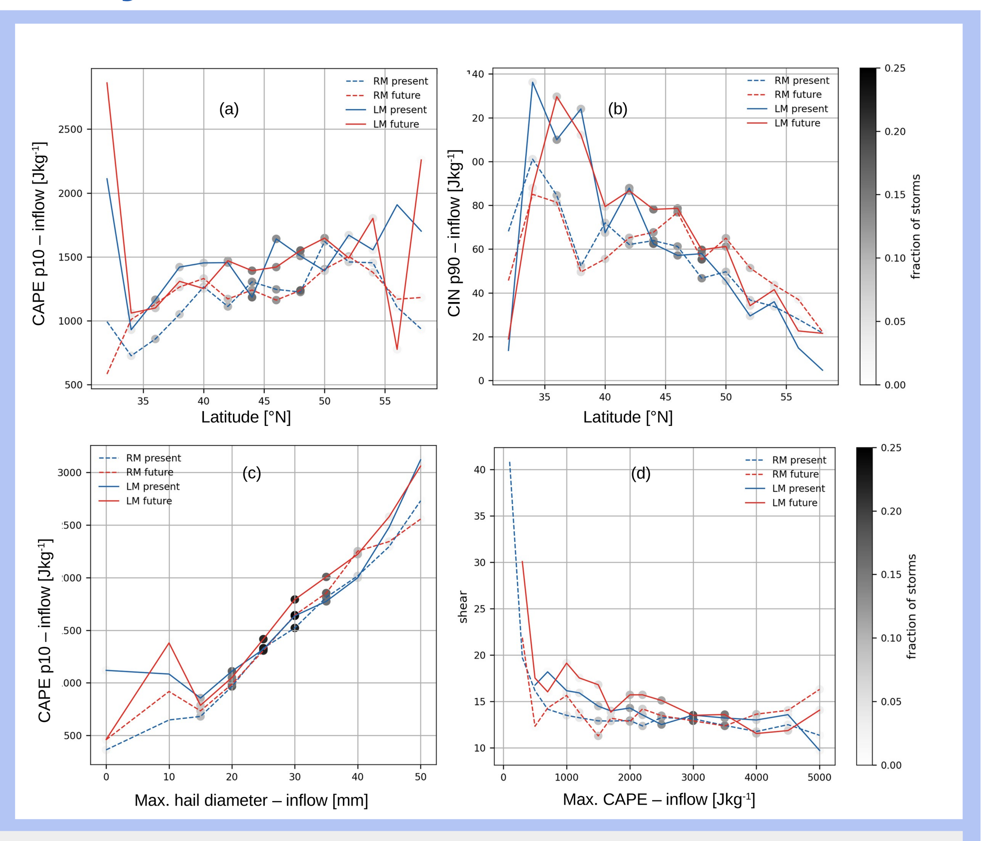


Figure 8 Conditions of inflow environments of supercells for the CTRL (blue) and PGW (red) simulation and left (solid lines) and right (dashed lines) moving storms: (a) 10th percentile of most unstable CAPE and (b) 90th percentile most unstable CIN vs. mean latitude, (c) 10th percentile of most unstable CAPE vs. maximum hail diameter and (d) 90th percentile of vertical wind shear vs. maximum most unstable CAPE of the super cell inflow region. The dots are coloured by the fraction of supercell storms in each bin.

7 Conclusions

- For hail storms, lower bounds of CAPE, CIN, vertical wind shear in pre-storm environments and freezing level within storm increase with +3°C global warming level
- Differences between supercell storm types (RM vs. LM) larger than between climate scenarios
- See also Poster P4: ECSS2025-30 on hail proxy comparison and trends with climate change

References

1 Mohr et al. (2015): Hail potential in Europe based on a regional climate model hindcast. GRL.
2 Battaglioli et al. (2023): Modeled Multidecadal Trends of Lightning and (Very) Large Hail in Europe and.... J. Appl. Meteor. Climatol.
3 Raupach et al. (2023): An Improved Instability–Shear Hail Proxy for Australia. Monthly Weather Review.
4 Kahraman et al. (2024): Climatology of severe hail potential in Europe based on a convection-permitting simulation. Clim Dyn.
5 Cui et al. (2025): A European hail and lightning climatology from an 11-year kilometer-scale regional climate simulation. JGR: Atmos.
6 Thurnherr et al. (2025): The effect of 3°C global warming on hail over Europe. GRL.
7 Adams-Selin and Ziegler (2016): Forecasting hail using a one-dimensional hail growth model within WRF. Monthly Weather Review.
8 Brogli et al. (2023): The pseudo-global-warming (PGW) approach: methodology, software package PGW4ERA5 v1.1… GMD.
9 Cui et al. (2023): Exploring hail and lightning diagnostics over the Alpine-Adriatic region in a km-scale climate model. WCD.
10 Malečić et al. (2023): Simulating hail and lightning over the Alpine Adriatic region.... JGR: Atmos.
11 Brennan et al. (2024): An object-based and Lagrangian view on an intense hailstorm day in Switzerland... WCD.
12 Brennan et al. (2025): Insights from hailstorm track analysis in European climate change... NHESS.
13 Feldmann et al. (2025): European supercell thunderstorms—A prevalent current threat and an increasing .... Science Adv.