Assessing the Impact of Hailstorms in a Future Climate (HailClim)

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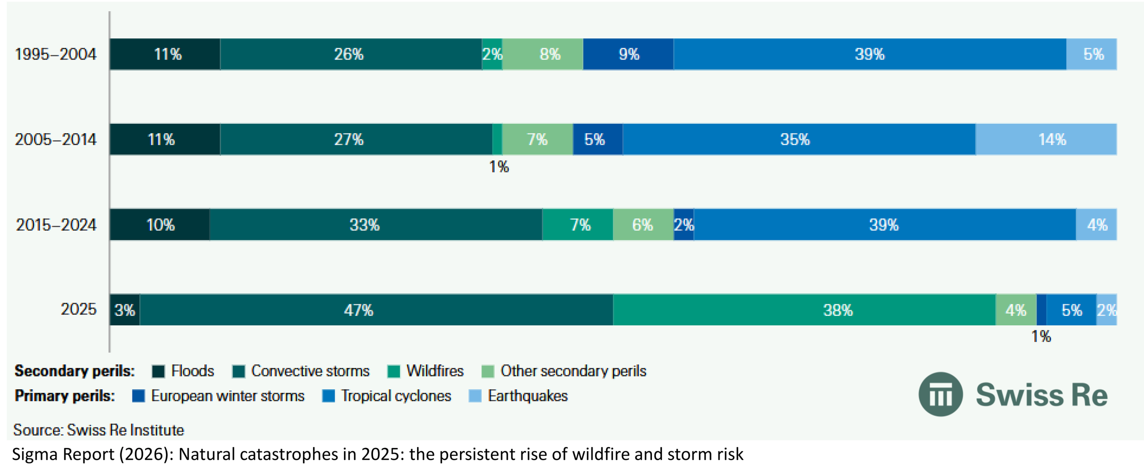
Motivation



- Severe convective storms (SCS) are among the natural catastrophes that cause the most global insured losses, with hail responsible for 50 – 80 % of these damages.
- Hail is affected by atmospheric instability, humidity, vertical wind shear and melting level height.
- Climate change has an influence on these parameters, however, the effect on the frequency and severity of hail events is still unclear.

Datasets

- Potential hail tracks (PHTs) from 3D radar network of German Weather Service (DWD; April – September, 2005 – 2024; Mohr & Tonn et al., 2026)
- Building damage data from German Insurance Association (GDV; 2005 – 2023)
- Convective parameters of ERA5 (0.25° spatial and 1h temporal resolution) calcaulated by thundeR package (available for 1990 – 2024; Taszarek et al., 2026)
- Climate model runs from NUKLEUS ensemble (historical, +2K and +3K period; Beier et al., 2025)

Potential hail tracks (PHTs)

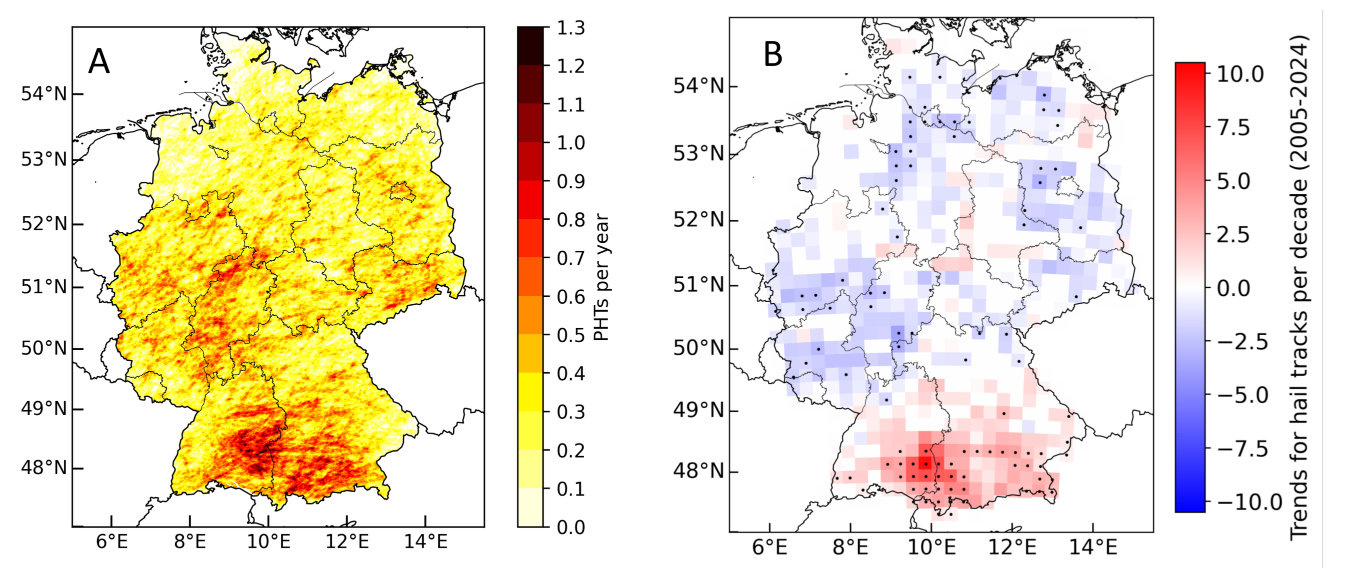


Fig. 1: (A) Mean annual number of 3D radar-derived potential hail tracks (PHTs) over Germany on a 1 km grid and (B) decadal trends of PHTs on a 25 km grid with black dots indicating statistical significance (2005 – 2024, April – September; Mohr & Tonn et al., 2026).

Tab. 1: Contingency table for calculating the skill of the PHTs using the GDV insurance data

	Damage	No Damage
PHT	A	B
No PHT	C	D

$$POD = \frac{A}{A + C}$$

$$FAR = \frac{B}{A + B}$$

$$HSS = \frac{2\,(AD - BC)}{(A + C)(C + D) + (A + B)(B + D)}$$

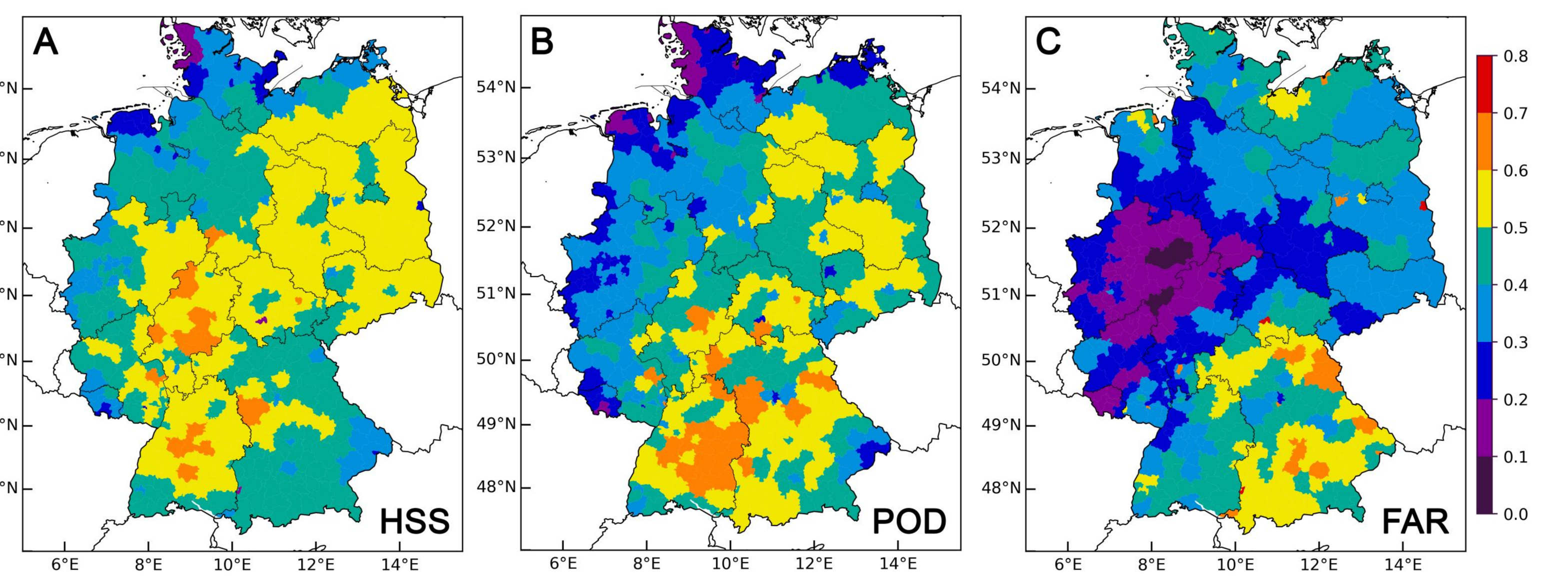


Fig. 2: Validation of radar-based PHTs using the district-based standard residential building insurance data from GDV based on (A) Heidke Skill Score (HSS), (B) Probability of Detection (POD) and False Alarm Ratio (FAR) for the period May 2005 to August 2023 (Mohr & Tonn et al., 2026).

Importance of combining wind shear with CAPE

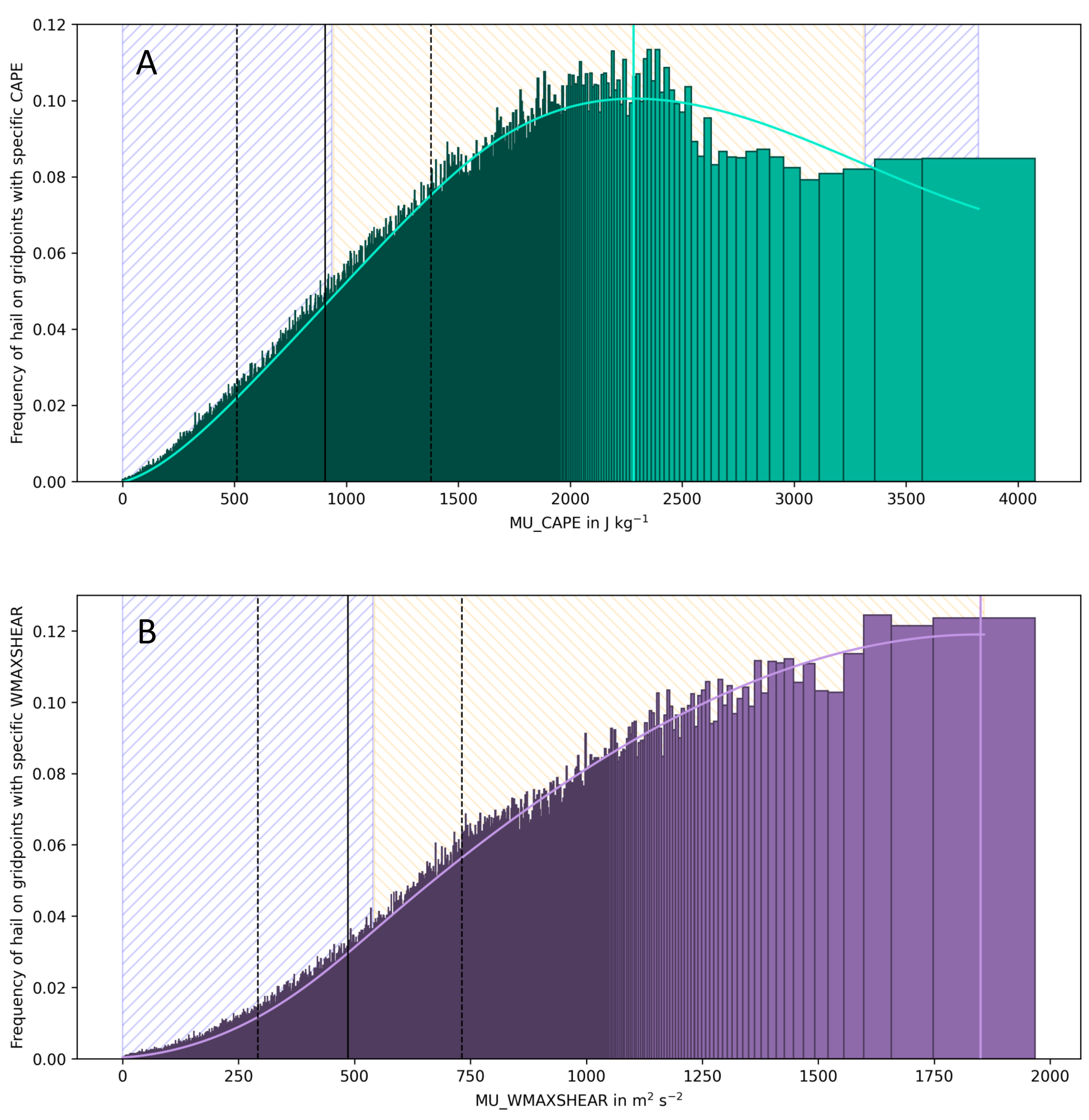


Fig. 3: Potential hail frequency as a function of (A) MU_CAPE and (B) MU_WMAXSHEAR considering all ERA5 grid point time steps within Germany at hourly resolution during the 20 summer half-years (2005 -- 2024). Each bar represents 5000 data points within a given value range. Consequently, bin widths increase towards higher values due to the decreasing number of available sample points. The light colored curve shows a 1D smoothing spline fit, with the vertical line indicating its maximum. Blue background shading indicates convex changes in hail frequency, while orange shading indicates concave behavior. Black vertical lines mark the 25th (dashed), 50th (solid), and 75th (dashed) percentiles of the variable distribution for hail data points (Tonn et al., submitted).

- Hail frequency reaches maximum for CAPE around 2200 J/kg, even higher instability leads to less hail.
- Best hail conditions occur in highest combined instability and vertical wind shear.

XGBoost model

- Use of a statistical model to combine hail events with convective parameters and to consequently estimate hail occurrence in climate models.

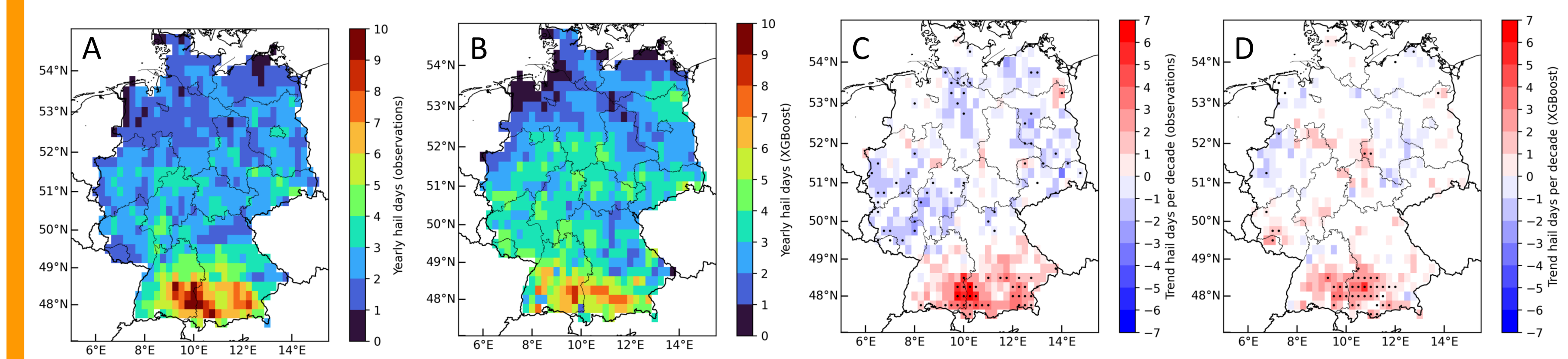


Fig. 3: Yearly hail days (A) from observations and (B) calculated by the XGBoost model (test period: April – September, 2019 – 2024), and trends in hail days per decade (C) from observations and (D) calculated by the XGBoost model (whole period: April – September, 2005 – 2024) on ERA5 grid.

Tab. 2: Convective parameters based on thundeR used in the XGBoost model (Chen & Guestrin, 2016) for estimating hail day occurrence.

HGT_ISO_002	Height of 0°C isotherm
ML_LI	Mixed-layer lifted index
SHIP	Significant hail parameter
ML_CAPE	Mixed-layer convective available energy
ML_WMAXSHEAR	Square root of two times ML_CAPE by surface to 6 km AGL bulk wind shear
K_Index	K_Index
PRCP_WATER	Precipitable water (entire column)
BS_ML_LCL_M10	Bulk wind shear between mixed-layer lifted condensation level and -10°C isotherm
orog	Topographic height

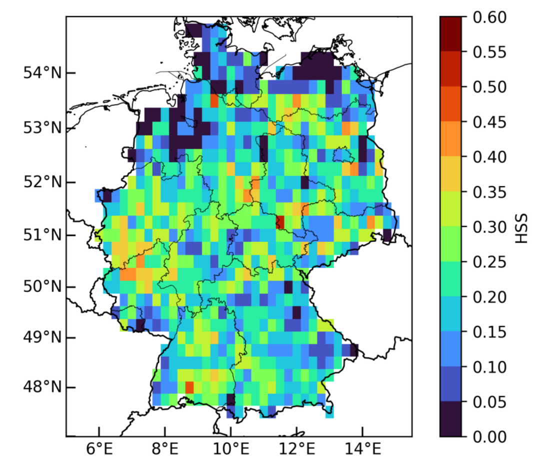
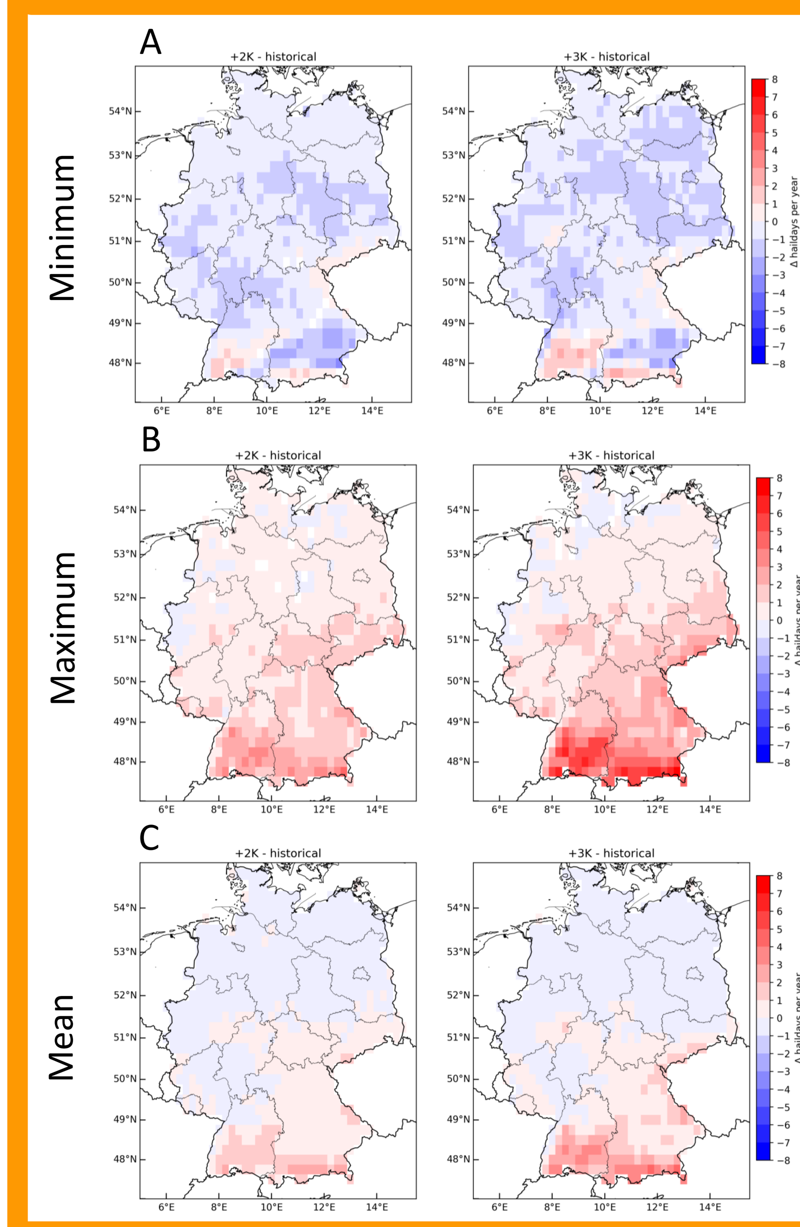


Fig. 4: Spatially resolved Heidke Skill Score (HSS) for prediction of hail days using the XGBoost model with a decision threshold of 0.93 for the test period 2019 – 2024.

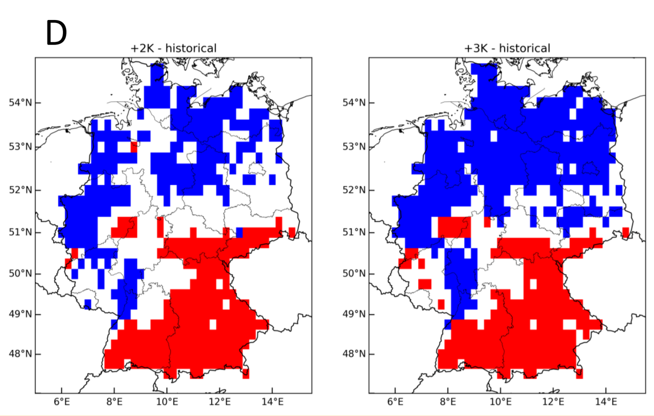
Hail anomalies in a warmer climate



Tab. 3: Ensemble members of NUKLEUS used for estimating future potential hail occurrence.

GCM	RCM	Scenario
EC-Earth3-Veg	ICON-CLM	ssp2-4.5
EC-Earth3-Veg	ICON-CLM	ssp3-7.0
EC-Earth3-Veg	ICON-CLM	ssp5-8.5
EC-Earth3-Veg	COSMO-CLM	ssp3-7.0
MIROC6	ICON-CLM	ssp3-7.0
MIROC6	COSMO-CLM	ssp3-7.0
MPI-ESM1-2-HR	ICON-CLM	ssp3-7.0
MPI-ESM1-2-HR	COSMO-CLM	ssp3-7.0

Fig. 5: (A) Minimum, (B) maximum and (C) mean anomalies for potential hail days between +2K and historical period (left) and between +3K and historical period considering 8 NUKLEUS ensemble members. (D) Grid points on which at least 6 of the 8 ensemble members show positive (red) or negative (blue) anomalies to visualize reliability.



Conclusions

- Hail can occur anywhere in Germany, but it is more common in the south. There has also been an increase in hailstorms in that region over the past 20 years, while the rest of the country has seen a tendency towards a decline.
- For convective conditions, a combination of vertical wind shear and atmospheric instability is important. Increasing instability alone does not result in more hail.
- A statistical hail model (XGBoost) was developed that estimates days with hail based on convective environmental conditions. While there are difficulties in accurately predicting individual days (HSS approximately 0.2), the model provides a good overall representation of climatology and trends.
- Applying the XGBoost model to climate data reveals a significant increase in the number of days with hail in southern Germany under a warmer climate. For most climate ensemble members, a weaker decrease is observed in northern Germany.
- Outlook: How does the hail risk changes with that change of hail hazard?

Literature

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