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Estimation of hail frequency and its trends under climate change using ML

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Motivation

Why do radar-identified hail events show negative trends over large parts of Germany during the last 20 years?

How can a proxy-based ML hail model be designed that reproduces observed hail trends?

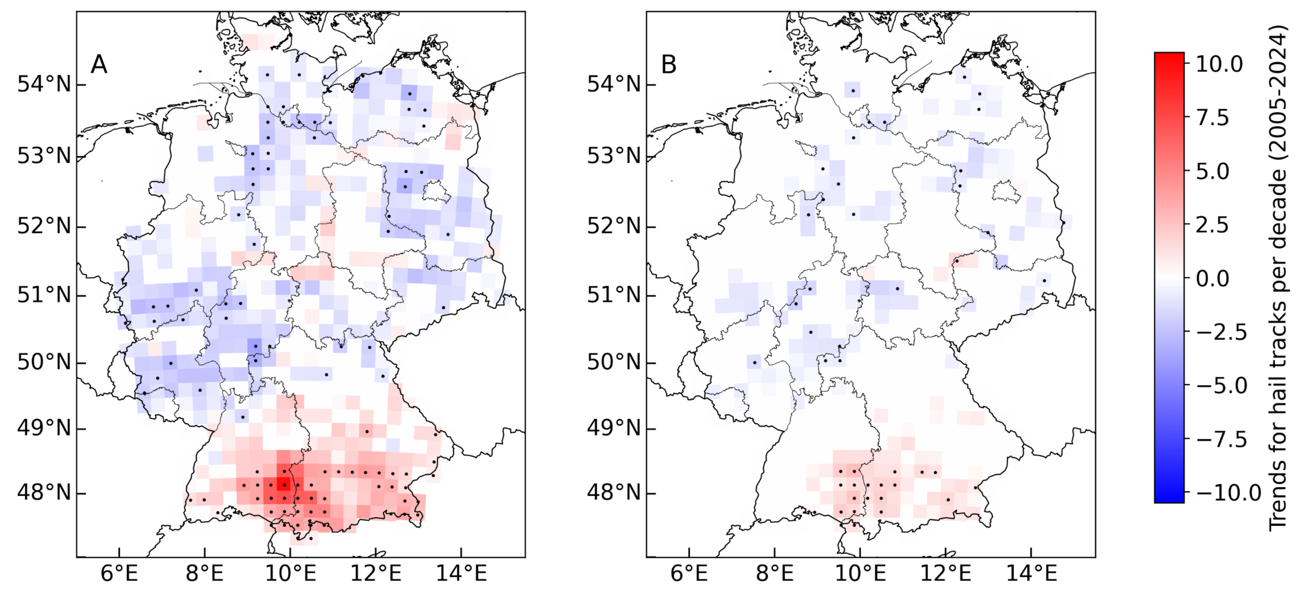


Fig. 1: (A) Decadal trends of all potential hail tracks and (B) of all tracks with a minimum length of 50 km for 20 years of hail data (2005 – 2024, April – September), Mohr et al. (2025).

Data basis

- Potential hail tracks identified from 3D radar network of German Weather Service (DWD; April – September, 2005 – 2024)
- Cloud-to-ground lightning data (EUCLID; summer half-years 2005 – 2023)
- Convective parameters of ERA5 (0.25° x 0.25° grid, hourly resolution) calculated by thunder package (available for 1990 – 2024; Taszarek et al., 2024)

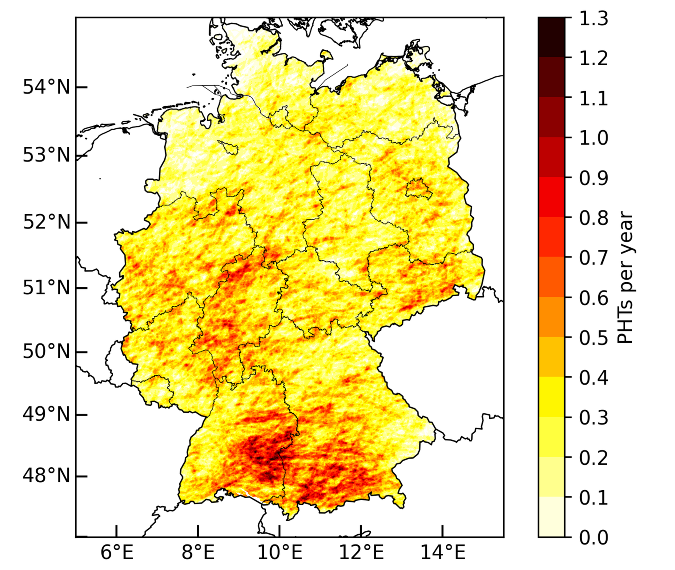


Fig. 2: Distribution of potential hail tracks over Germany on a 1 km grid (2005 – 2024, April – September).

Proxy based hail model

Table 1: Convective parameters of ERA5 used as predictors in logistic regression and XGBoost hail day model

MU_CAPE	*most-unstable convective available potential energy*
MU5_E_LI	*most-unstable entrainment lifted index at 500 hPa*
MU_LI	*most-unstable lifted index*
RH_500850	*mean rel. humidity between 500 & 850 hPa*
MU_MIXR	*mixing ratio at height of MU parcel*
MU_cold_cloud	*layer depth between -10°C and equilibrium level*
LR_16km	*temperature lapse rate between 1 and 6 km AGL*
PRCP_WATER_eff	*effective precipitable water acounting for RH*
BS_06km	*bulk wind shear between surface and 6 km*
SRH_03km_RM	*storm-relative helicity between surface and 3 km*

Better performance of **XGBoost model** compared to logistic regression:

Table 2: Optimum splitting threshold and quality measures for both logistic regression and XGBoost model

	Logistic Regression	XGBoost
Best threshold for splitting	0.73	0.79
Area under precision-recall curve	0.399	0.440
Matthew's correlation coefficient	0.441	0.460

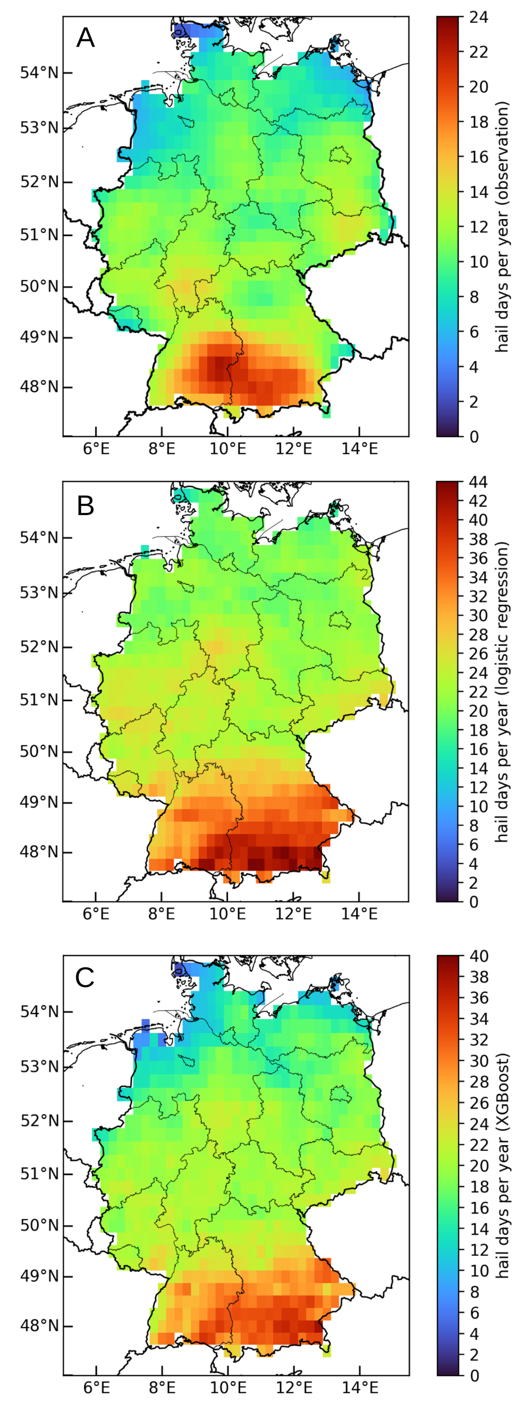


*Fig. 3: Hail days per year (A) observed, (B) modeled with **logistic regression**, and (C) **XGBoost** on 0.25° grid resolution.*

- **Models represent overall structure of hail distribution with hotspots in hail frequency in southern Germany and a strong gradient from north to south**
- **Models overestimate the number of hail days**
- **XGBoost model better represents the lower frequencies in northern Germany**
- **Models fail in representing the correct trends**

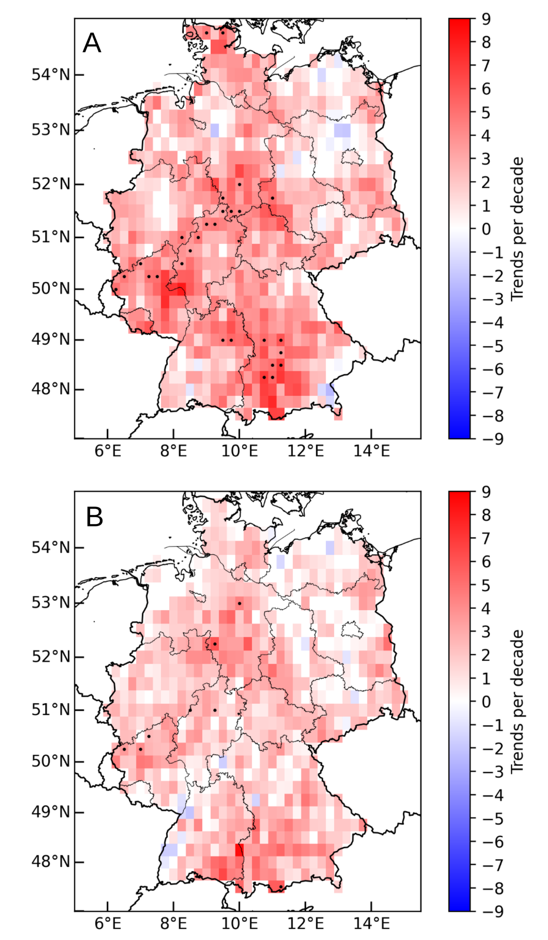


*Fig. 4: Trends per decade of hail days per year modeled with (A) **logistic regression** and (B) **XGBoost** on 0.25° grid resolution.*

Application to climate models

Use of NUKLEUS ensemble:

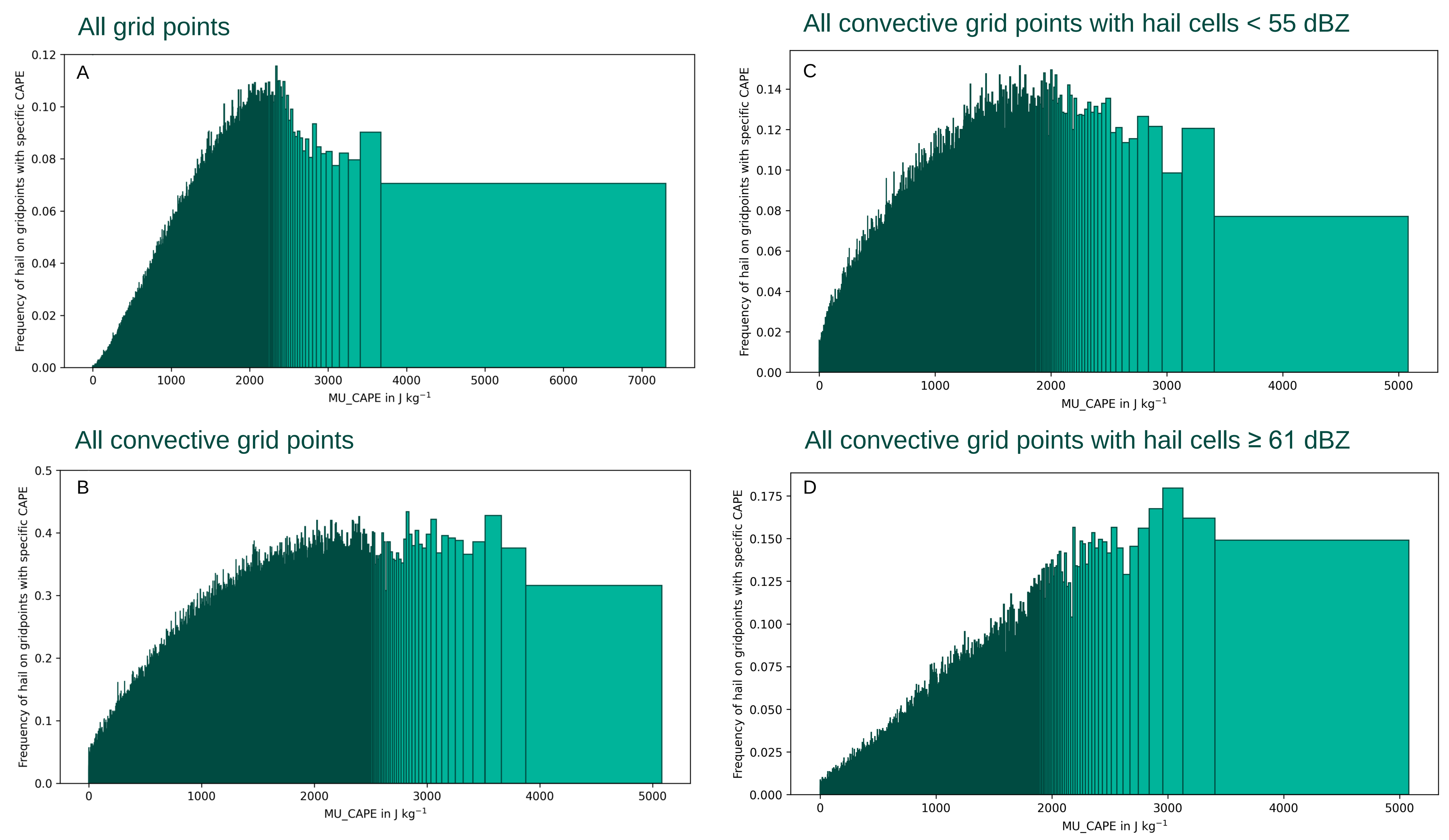
Consists of regional downscaling of 3 CMIP6 GCMs:
1) EC-Earth3-Veg
2) MPI-ESM-HR
3) MIROC6

With 3 regional climate models:
1) ICON-CLM
2) COSMO-CLM
3) REMO

Data available for 3 and 12.5 km grid spacing for historical period and +2K and +3K global warming level

Higher instability – higher hail occurrence?

Fig. 5: Hail frequency for grid points with specific most-unstable CAPE over Germany according to ERA5 parameters (thundeR; Taszarek, 2024) and potential hail tracks. A grid point is counted as hail gridpoint if there is a cell detection within a radius of 50km from 30min before to 30min after the time step. Each bar of a plot contains the same number of grid points (for A: 5000, for B, C and D: 500).
(A) All grid points are considered (hourly resolution; April – September 2005 – 2024)
(B) Only grid points with convection are considered (hourly resolution; April – September 2005 – 2023); convective grid points are defined by 5 cloud-to-ground lightning strokes within a radius of 50km from 30min before to 30min after the time step
(C) Same as (B), but identified hail cells have only low reflectivities in the precipitation scan (< 55 dBZ)
(D) Same as (B), but identified hail cells have high reflectivities in the precipitation scan (≥ 61 dBZ)



- **No further increase in hail potential for increasing CAPE above ~ 2000 J/kg**
- **For lower reflectivity: maximum hail potential is reached at lower CAPE values and higher CAPE reduces hail potential clearly**
- **For higher reflectivity: maximum hail potential is reached at higher CAPE values**

Literature

- Mohr, S., M. Tonn, M. Augenstein, C. Sperka, G. Kavil Kambrath, M. Kunz (2025): A 20-year spatio-temporal analysis of 3D radar-based hail tracks in Germany: Trends and regional differences. Handed in in Frontiers in Environmental Science.
- Taszarek, M., B. Czernecki, P. Szuster (2024): ThundeR – A rawinsonde package for processing convective parameters and visualizing atmospheric profiles.