A 20-year spatio-temporal analysis of 3D radar-based hail tracks in Germany: Trends and regional differences

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Hail track statistics

- Hail hazard across Germany varies due to the influence of large-scale climate and regional orography.
- Highest frequency of PHTs in southern Germany and downstream of low mountain ranges.
- 20-year radar-based climatology consistent with previous studies using shorter time periods.

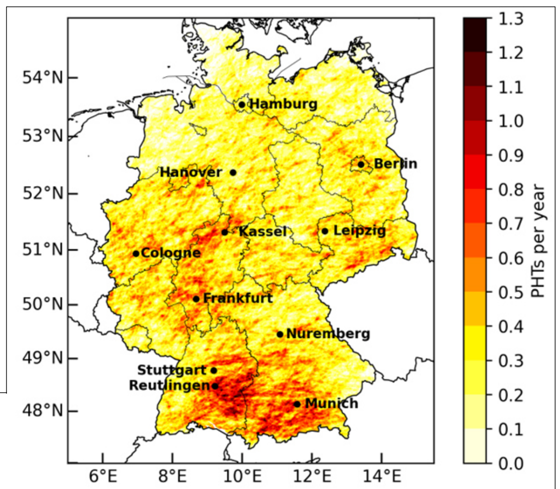


Fig. 2: Mean annual number of 3D radar-derived potential hail tracks (PHTs) per 1×1 km² in Germany (2005 – 2024, SHY; Mohr et al., 2025).

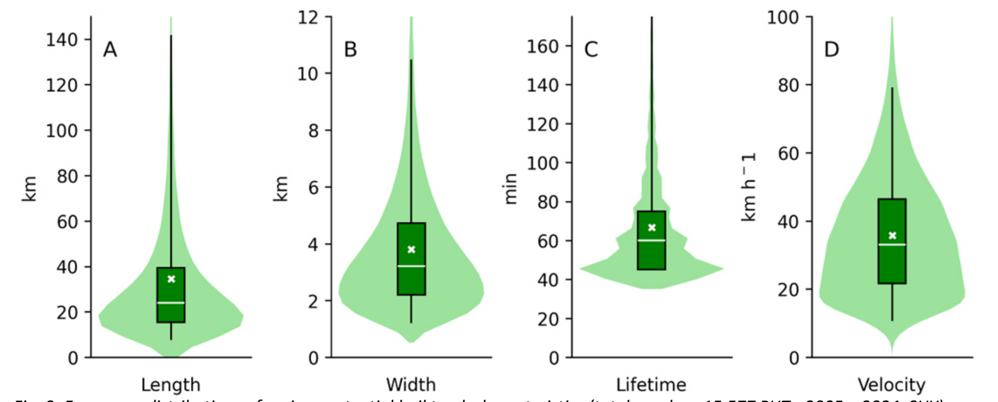


Fig. 3: Frequency distributions of various potential hail track characteristics (total number: 15,577 PHTs, 2005 – 2024, SHY): (a) Track length in km, (b) track width in km, (c) track lifetime in min (15 minutes resolution), (d) mean track speed in km h^{-1}. The interquartile range is represented by the boxes, the median by the white line, and the mean by the white cross. Whiskers display the 2nd and 98th percentiles. Few events exceed the shown range of values. Maxima for the respective characteristics are: (a) 446 km, (b) 34 km, and (c) 525 min (Mohr et al., 2025).

Clustering and relation to atmospheric pattern

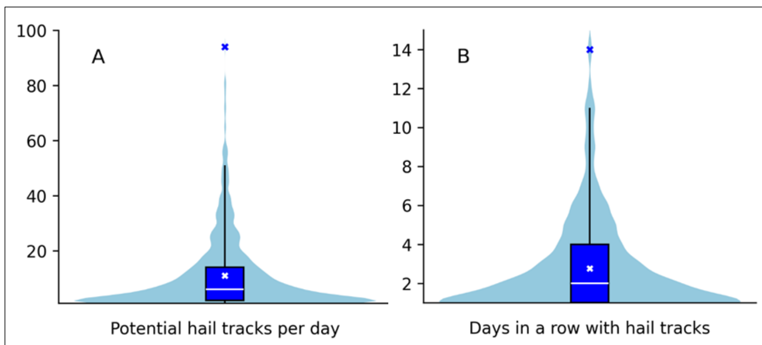


Fig. 4: (a) Frequency of potential hail tracks (PHTs) per day across Germany. (b) Clustering of PHTs over consecutive days across Germany. The box represents the interquartile range, while the whiskers indicate the 2nd and 98th percentiles. The median is shown as a white line, the mean as a white cross, and the maximum value as a blue cross (Mohr et al., 2025).

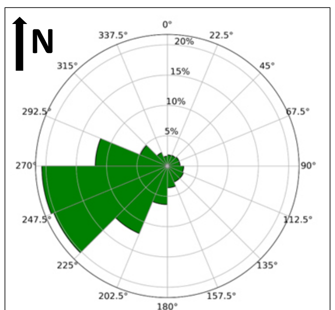


Fig. 5: Frequency distribution of track motion direction in ° for all 15,577 PHTs (2005 – 2024, SHY; Mohr et al., 2025).

- **Spatial clustering**: There are occasional periods of intense hail activity with many tracks per day; 30 % of hail days featuring more than ten PHTs.
- **Temporal clustering**: Hail events are unevenly distributed in time (63 % of days without PHTs), often clustering under favorable large-scale flow conditions. About 42 % of PHT days are isolated, while two- to three-day clusters are common, and rare persistent episodes can last up to two weeks during prolonged blocking.
- **Atmospheric blocking**: Half of all PHT days occur during blocking regimes, which favor convection and sustain multi-day hail hazards.

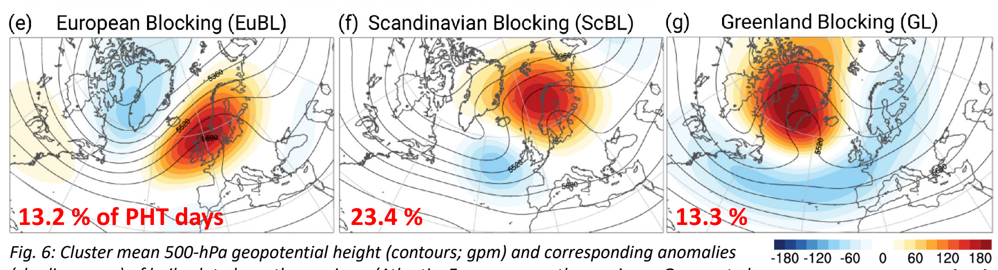
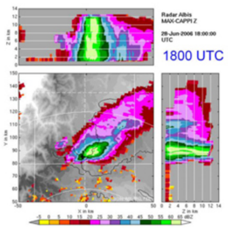


Fig. 6: Cluster mean 500-hPa geopotential height (contours; gpm) and corresponding anomalies (shading; gpm) of hail-related weather regimes (Atlantic–European weather regimes; Grams et al., 2017, Büeler et al., 2021), as well as the relative share of each specific weather regime on PHT days (shown in red).

Motivation & data & methods

(1) What are the **patterns** of hail occurrence in Germany and what meteorological or geographical factors influence its distribution?
(2) What are the **characteristics** of hail tracks and are there long-term **trends** in their occurrence?
(3) Are there temporal **clusters** in hail events and which **large-scale atmospheric patterns** favor their formation?

- Data basis: **3D radar data (PZ product)** of *Deutscher Wetterdienst* (DWD)
- Period: **2005 – 2024** (summer-half year, SHY)
- **Method**: Radar-based cell detection and tracking algorithm **TRACE3D** (Handwerker, 2002) modified by Schmidberger (2018)



→ 15 577 Potential hail tracks (PHTs)

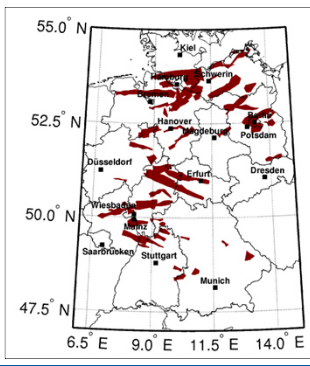


Fig. 1: Visualization of potential hail tracks (PHTs) as polygon tracks, detected by TRACE3D on 15 July 2015 (Schmidberger, 2018).

Trends

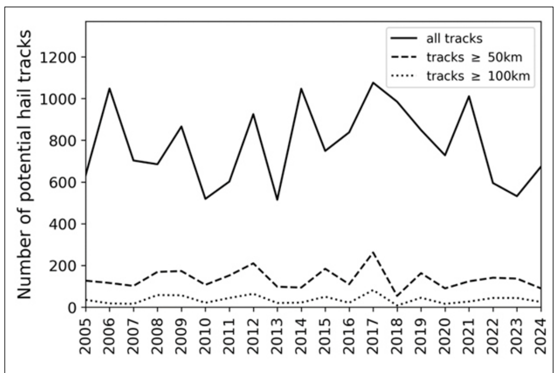


Fig. 7: Time series of the annual total number of potential hail tracks (PHTs) across Germany (2005 – 2024, SHY). Different line types represent all tracks (solid) and those with a specific minimum length (dashed: 50 km, dotted: 100 km; Mohr et al., 2025).

- **Entire Germany**: High annual variability in PHTs with **no clear trend.**
- **Regional contrast**: Northern and central Germany show no or decreasing trends, whereas southern Germany exhibits a significant increase.
- **Unexpected**: Contradicts the common assumption that higher temperature and moisture lead to more SCSs.

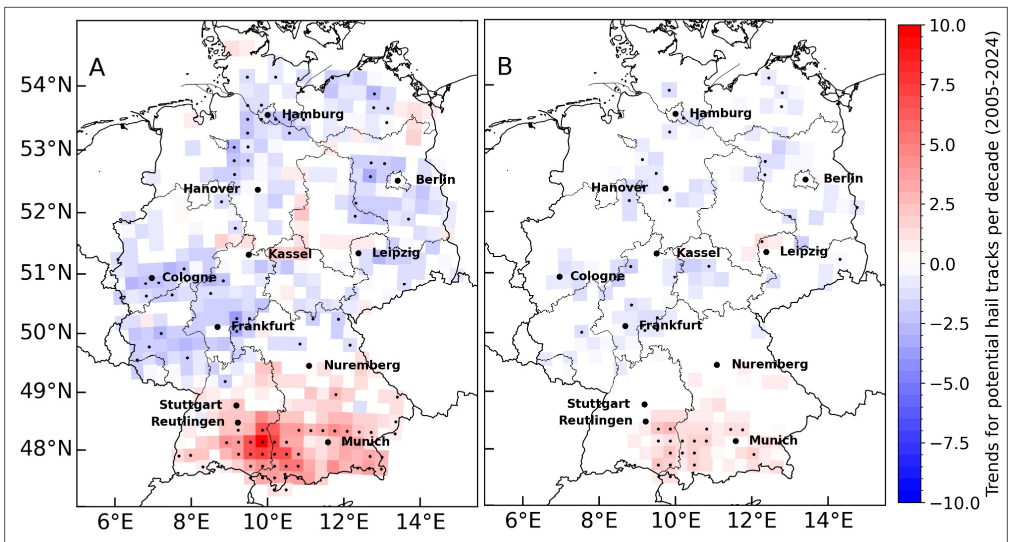


Fig. 8: Spatially resolved trends (<u>per decade</u>) of potential hail tracks (PHTs, 2005 – 2024, SHY) per 25×25 km²: (a) All PHTs across Germany and (b) PHTs with a minimum length of 50 km. Small points indicate statistical significance at the 0.05 level according to the Mann-Kendall test (Mohr et al., 2025).

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Mohr, S., Tonn, M., Augenstein, M., Sperka, C., Kavil Kambrath, G., Kunz, M. (2025): A 20-year spatio-temporal analysis of 3D radar-based hail tracks in Germany: Trends and regional differences. *Front. Environ. Sci*. (Submitted).