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Advances and challenges in hail research: report from the 4th European hail workshop 2024

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Hailstorms cause substantial damage to buildings, crops, vehicles, and infrastructure in many regions worldwide. Despite notable progress in recent years, hail remains insufficiently understood and poorly represented in numerical weather prediction models and risk assessments. The 4th European Hail Workshop (2024) showcased advances in detection, forecasting, climatology, and impact assessment of hail, while highlighting key challenges that remain. Progress in remote sensing, weather prediction, and seamless forecasting has improved early detection of hail events, extended forecast lead times, and enhanced warning capabilities. Field campaigns and laboratory experiments are yielding new insights into hailstone characteristics, hail formation processes, and impacts. Studies of storm dynamics and microphysics emphasized the complex interactions of processes involved across a wide range of temporal and spatial scales. Finally, artificial intelligence and machine learning are opening new avenues for hail detection, prediction, and risk modeling, marking a shift toward more integrated and innovative approaches in hail research.

KEYWORDS

hail, hailstorms, hail damage, hail climatology, hail detection, hail forecasting, microphysics, AI/ML

1 Overview

The 4th European Hail Workshop (https://ehw2024.imk-tro.kit.edu), held from 5 to 7 March 2024 in Karlsruhe, Germany, was jointly organized by the Karlsruhe Institute of Technology (KIT), the Mobiliar Lab for Natural Risks of the Oeschger Centre for Climate Change Research at the University of Bern, MeteoSwiss and the German Weather Service (Deutscher Wetterdienst, DWD). The event brought together over 180 scientists and experts from 23 countries, representing atmospheric research, weather services, insurance, economics, and agriculture (Figure 1). The interdisciplinary audience underscored the global importance and relevance of hail-related impacts.

The primary objectives of the workshop were to identify and discuss key topics in both fundamental and applied research, and to promote exchange of ideas and data. In addition, the workshop aimed to foster new collaborations, and to further strengthen the international hail research community.

FIGURE 1
Hailstone observations during the field campaign ICECHIP in May/June 2025 in the United States (Photo by S. Mohr, KIT).

The workshop was organized into seven sessions, with the last two introduced for the first time:

1. Convection and hail in a changing climate
2. Hail damage and damage prevention
3. Hail climatology, risk, and loss
4. Hail detection and forecasting
5. Microphysics and dynamics of hailstorms
6. Hail research and AI/ML
7. Field campaigns

Additional highlights were the two panel discussions: *The Truth Aloft: Collecting New Data through Field Campaigns* and *Teaching and Research in Meteorology in the Age of Artificial Intelligence (AI)*, the latter organized by Early Career Scientists. These two topics are expected to shape some of the most dynamic developments in hail research in the coming years. After the fully virtual 2021 edition due to the COVID-19 pandemic, the 2024 workshop was held in hybrid format, with the vast majority of participants attending in person.

This paper summarizes the presentations given at the workshop, focusing on key findings and novel approaches in hail research. Where available, we referenced peer-reviewed publications by the presenters that are directly related to their talks and published around the time of the workshop. This may help readers access further topic-specific information and identify statements supported by peer-reviewed evidence.

2 Session reports

2.1 Convection and hail in a changing climate

Assessing potential changes in hailstorm frequency and severity in response to climate change remains highly challenging. Uncertainty arises from the limited availability of direct hail observations (e.g., hailpads or automatic hail sensors), the relatively short record of remote sensing data used as hail proxy (radar and satellite), and the unclear response of environmental conditions (e.g., prevailing weather patterns) and microphysical processes (e.g., aerosol concentrations) to a warming climate (Raupach et al., 2021). Moreover, it is still unclear how changes in the convective environment translate into changes in storm frequency, storm intensity, and hail production.

For many regions both reanalyses and climate model projections indicate an increase in hail-conducive conditions, which is translated into more severe hail events by statistical models. For northern Italy, for example, an additive logistic model based on ERA5 reanalysis reveals a significant trend toward more severe convective storms and associated phenomena (Battaglioli et al., 2023). However, hailpad observations in the same region show no significant trend in hail day frequency, and only a modest increase in very large hail occurrences (Manzato et al., 2025; 2022).

Convection-resolving climate model simulations offer additional insights into how hailstorm characteristics, such as size, frequency, clustering, and storm life cycle, may evolve under different climate scenarios (Cui et al., 2025; Kahraman et al., 2024). Kilometer-scale regional simulations, for example, suggest for a 3 K warming scenario an increase in the annual number of hail days in central and eastern Europe and a decrease in southern and western Europe during the warm season (Thurnherr et al., 2025; Cui et al., 2025). Simulations of past hail events in the United States using the pseudo-global warming (PGW) framework predict increases in hail size for the cold season (December to February) compared to the historical simulations. On the other hand, warm season PGW simulations (June to August) show a decrease in hail sizes and hailfall area. This decrease is likely due to enhanced warm-rain processes that produced a greater number of hail embryos competing for supercooled liquid water (Mallinson et al., 2024; Lasher-Trapp et al., 2023). The shift in hail-prone conditions from warmer to cooler regions is crucial for accurate predictions of future hail frequency.

FIGURE 2
Participants of the European Hail Workshop at the venue at KIT.

However, due to the high sensitivity of model results to variations in microphysics and the change signal in PGW, a more comprehensive framework with large ensembles is required.

2.2 Hail damage and damage prevention

Hail damage has been assessed either at the event-scale through on-site investigations of hailstone characteristics (Farnell Barqué et al., 2024) and material vulnerabilities (Meisenzahl et al., 2025), or across several years. The latter was done by combining radar-derived products with insurance loss data and crowd-sourced reports to identify hail-prone regions and key factors contributing to hail damage to buildings (Schmid et al., 2025; 2024) and crops (Portmann et al., 2024).

Recent advancements in this field have been accelerated by the application of Machine Learning (ML) techniques (see also Sect. 2.6). For example, ML algorithms used to generate synthetic hail event sets for risk assessments have demonstrated improved accuracy in estimating location-specific hail risk. A particularly successful approach to estimate hail damage involves linking radar-based Maximum Estimated Size of Hail (MESH), insurance claims, and storm-specific meteorological information (Schmid et al., 2025; Ackermann et al., 2023). Multi-year analyses reveal that longer-lasting hailstorms are associated with greater cumulative damage (Ackermann et al., 2023).

The lack of detailed (forensic) investigations of hail damage results in knowledge gaps concerning specific characteristics of damaging hailstorm and corresponding damage patterns. While loss documentation tends to focus on extreme hail events, the more common sub-severe events–which still cause considerable damage to roofs and crops–are often under-reported (Meisenzahl et al., 2025).

2.3 Hail climatology, risk, and loss

Recent advances and novel methods used for constructing hail climatologies (e.g., Wilhelm et al., 2024), risk assessments, and loss modeling (e.g., Schmid et al., 2025) have considerably enhanced our understanding of the spatio-temporal variability of hailstorms. A key challenge emphasized throughout the session is the scarcity of high-resolution, long-term, and homogeneous hail observations, which also hampers reliable estimates of trends related to climate change. Furthermore, understanding the co-occurrence of hail with other weather phenomena, such as heavy rainfall or strong winds, is essential, as such compound events can substantially exacerbate damage. An analysis over Alberta's (Canada) "hail alley" using radar and ground-based observations suggests that the impact of joint occurrences of wind-driven hail and hail–rainfall events is underestimated by 20% and 70%, respectively, when assuming independence (Mohamed et al., 2024). Although such compound events can have substantial implications for risk assessment and management, they remain insufficiently explored.

National radar-based hail climatologies are now available for several European countries, including the United Kingdom (United Kingdom; Wells et al., 2024), Switzerland (Wilhelm et al., 2024), Austria (Ehrensperger et al., 2025), Germany, or Greece. The hail hazard assessments also allow for tracking of hail cell dynamics, providing additional insights into storm characteristics such as timing, intensity, and cell tracks. The radar-based hail climatology for the United Kingdom, for example, has shown that supercells dominate severe hail events even in a maritime climate (Wells et al., 2024). In addition to radar, spaceborne passive microwave retrievals can be used to estimate regional (Galligani et al., 2024) or global hail climatologies. These methods, however, face limitations in relating satellite-detected hail signals to surface-based observations, especially in tropical regions.

A promising approach for detailed hail hazard and risk mapping involves ML modeling based on large datasets (see Sect. 2.6). A global ML hail model demonstrated that combining data from United States and Europe leads to improved predictive skill for hail occurrence. Additionally, seamless coupling of kilometer-scale weather prediction models with climate simulations offers new opportunities for reconstructing historical hail events–including tracking of simulated cells–and assessing associated impacts (Brennan et al., 2025). Results have been incorporated into the hail impact assessment platform scClim for Switzerland, developed in collaboration with multiple stakeholders (https://scclim.ethz.ch).

2.4 Hail detection and forecasting

This session addressed a broad spectrum of topics, including recent advances in numerical weather prediction (NWP), nowcasting, remote sensing, and statistical verification. A central topic was the growing capability of seamless forecasting systems that integrate multiple observational and modeling approaches. Recognizing the role of large-scale flow conditions and weather patterns in severe hailstorm predictability was shown to improve lead-time for warnings.

DWD's Seamless INtegrated FOrecastiNg sYstem (SINFONY; see https://www.dwd.de/EN/research/researchprogramme/sinfony_iafe/sinfony_en_node.html), for example, leverages ensemble approaches to improve convective hazard warnings for lead times of up to 12 h. MeteoSwiss has advanced its Thunderstorms Radar Tracking (TRT) system by integrating severity ranking, lightning-jump detection, and polarimetric parameters, enabling more precise storm classification and automated warnings.

Advances in remote sensing have refined hail detection capabilities. Passive microwave satellite retrieval are useful for estimating hail climatologies, but still deviate from surface observations (Galligani et al., 2024). The latest Global Precipitation Measurement (GPM) version of dual-frequency precipitation radar includes a new hail detection algorithm that improves global hail assessments (Le and Chandrasekar, 2023). Satellite observations of overshooting tops (OTs) provide insight into updraft characteristics relevant to hail severity (Berman et al., 2024). While MESH-based hail size correlates positively with OT depth (linked to updraft speed), its weak negative relation with OT area and stratospheric lapse rate suggests control by updraft width. For United States Great Plains hailstorms, radar variables within the detected updraft, such as minimum copolar cross-correlation coefficient in mid-level updrafts, help distinguish small from severe hail (Klaus and Krause, 2024). For giant hail (≥ 10 cm), the best indicator is the reflectivity area ≥ 50 dBZ in the upper portion of the updraft.

Verification and recalibration of radar-based metrics have gained increasing attention. In Switzerland, crowd-sourced hail reports were used to recalibrate the radar-based Probability of Hail (POH) metric (Schmid et al., 2025; Kopp et al., 2024). Polarimetric radar features, such as differential reflectivity (ZDR) columns, show promise for estimating hail size. ML methods, especially Random Forest, were shown to improve hail size predictions (Aregger et al., 2025).

Beyond short-term forecasts, several studies have linked hailstorm occurrence to convection-related large-scale environments. European analyses show long-lived storms coincide with fast motion and strong shear, while larger hail occurs in buoyant, sheared conditions. Severe convective outbreaks are increasingly connected to heatwaves in Europe (Feldmann et al., 2025). A case study of the July 2023 Italy hailstorms (19 cm) found mid-tropospheric southwesterlies more important than instability alone (De Martin et al., 2025), consistent with evidence that wide updrafts favor giant hail (Lin and Kumjian, 2022).

2.5 Microphysics and dynamics of hailstorms

Despite advances in observational techniques and NWP, modeling hail formation, growth, remains a major challenge. Key uncertainties persist in cloud microphysics (e.g., Tonn et al., 2025), hail growth mechanisms including trajectories (Fischer et al., 2025), hail melt and resulting terminal velocity (Vagasky et al., 2025), and environmental initial conditions (Groot et al., 2024).

Large-ensemble simulations show that storm structure is mainly controlled by initial conditions, while hail formation and size distributions are strongly affected by concentrations of cloud condensation nuclei (CCN) and ice-nucleating particles (INP) (Groot et al., 2024; Ma and Li, 2024). However, sensitivity to these parameters varies widely, underscoring the need for refined bulk microphysics schemes. NWP models still struggle to accurately represent small-scale microphysical processes, limiting predictions of hailstorm intensity and duration.

Unresolved issues include the efficiency of secondary ice production, especially through rime-splintering (Seidel et al., 2024). Laboratory experiments have failed to reproduce previously reported high ice particle counts, questioning the validity of proposed mechanisms. Hailstone melting is another key uncertainty, as shape, wind, and humidity strongly influence fall speeds (Vagasky et al., 2025; Lin et al., 2024), shedding of meltwater, and melting rate. By integrating in-cloud hail size observations with a melt-only configuration in the 1D hail growth model HAILCAST (Adams-Selin and Ziegler, 2016), it is found that hailstones initially smaller than 10 mm require unrealistically cool or dry conditions to reach the surface (Vagasky et al., 2025). In contrast, larger hailstones in tropical environments can persist through melting. These findings highlight greater uncertainties in simulated hail characteristics than previously recognized.

Observations further show high variability in hailstone internal structures within the same storm, complicating generalizations (Farnell Barqué et al., 2024).

To address these gaps, researchers presented new approaches including isotopic analysis (Lin et al., 2025), high-speed imaging, and spectroscopy (Bernal Ayala et al., 2024). These laboratory investigations provided new insight into hailstone composition. Furthermore, they revealed spatial variations in non-soluble particle content, shedding light on aerosol contributions to hail nucleation and growth. Hailstone shape and melting dynamics were shown to affect trajectories and size distributions (Fischer et al., 2025; Lin et al., 2024). Wind tunnel experiments (Theis et al., 2025;

2022) indicate that current models underestimate drag coefficients of realistic hailstones that undergo melting, leading to overestimated terminal velocities and melting rates. Three-dimensional replicas of natural hailstones enable the retrieval of reliable information on fall speed, Reynolds number, and drag coefficient. (Theis et al., 2025).

Trajectory modeling shows oblate hailstones follow different paths than spherical ones, affecting size distributions (Lin et al., 2024). Studies based on HAILCAST (Adams-Selin and Ziegler, 2016) suggest spherical hailstone trajectories lead to more small hailstones but fewer very large ones compared to oblate hailstone trajectories. This is because larger spherical stones remain longer in strong updrafts compared to oblate ones (Adams-Selin, 2025; 2023).

2.6 Hail research and AI/ML

This session showcased diverse ML applications, including damage and risk assessment (e.g., Ackermann et al., 2023), satellite or radar data interpretation (e.g., Klaus and Krause, 2024), drone-based photogrammetry (Portmann et al., 2025; Lainer et al., 2023), and modeling hail size distributions (Ferrone et al., 2024). ML methods are becoming integral to hail research, addressing challenges in data quality, prediction accuracy, and impact assessment.

A major obstacle for ML applications is the limited availability and spatial coverage of high-quality hail observations, which hampers model training and validation (Schmidt et al., 2024; Scarino et al., 2023). Observational biases can further reduce robustness. To mitigate these issues, data preprocessing methods, such as Self-Organizing Maps, have proven effective for improving dataset consistency and predictive skill. Among the models presented, eXtreme Gradient Boosting (XGBoost) consistently outperformed parameter-based approaches in predicting large hail across varying environmental conditions. Higher-order deep learning models, such as convolutional neural networks (CNN), can enhance prediction and feature detection. The application of CNN, however, remain limited by the need for extensive training datasets.

ML applied to long-term datasets enables trend analysis and assessment of interannual variability, offering new insights into hail hazard evolution. For example, a double-moment normalization method sensor network showed that meteorological factors, rather than sensor-specific characteristics, primarily control distribution shapes.

2.7 Field campaigns

Data collected in real storm environments is essential for advancing our understanding of hail formation. High-quality observations not only help unravel the complex dynamics in hail formation and growth but can also serve as benchmarks for model development and evaluation. In recent years, several field campaigns have targeted hailstorm initiation, hailstone growth, and hailstone trajectories (e.g., Northern Hail Project in Canada (https://uwo.ca/nhp/) ICECHIP in the United States (Figure 2; https://icechip.niu.edu/), or LIFT in Germany (https://www.imk-tro.kit.edu/english/14_12545.php)). These campaigns increasingly benefit from advanced observational techniques and convection-permitting models. A key challenge remains the real-time capture of hailstorms, which requires continuous monitoring and rapid adaptation of observation strategies (Adams-Selin et al., 2024). Field operations are further complicated by the need to deploy sensitive instrumentation under often harsh conditions.

Novel approaches include lightweight, hail-shaped sondes ("hailsondes") designed to mimic hailstone trajectories and to measure temperature and humidity profiles in updrafts (Soderholm et al., 2025). Initial deployments of the hailsondes revealed complex curved paths and vertical velocities exceeding 50 m s^{-1}. Retrieved temperature and moisture profiles help identify dominant hail growth regimes (wet vs. dry growth). Unmanned aerial vehicles (UAVs) with multispectral and thermal imaging enhance hail swath detection. Isotope analysis and computer tomography (CT) scans can provide insights into hailstone structure, growth regimes, and air mass origins (Lin et al., 2025; Farnell Barqué et al., 2024). Analyses show distinct internal layering linked to humidity and temperature variability (Farnell Barqué et al., 2024). Finally, forensic hail damage surveys aim to establish a standardized hail intensity scale, analogous to the Enhanced Fujita (EF) scale for tornadoes. This approach requires extensive validation and cross-disciplinary collaboration.

3 Perspectives, needs, and outlook

In recent years, hail research has advanced considerably, driven by the growing economic impact of hail, now ranking as the second most damaging peril after tropical cyclones (SwissRe, 2024). At the same time, technical developments–such as high-performance computing enabling high-resolution simulations with large ensembles, dual-polarization radar, high-resolution satellite systems, and the growing use of ML models–have expanded research capabilities in hail detection, forecasting, climatology, and risk assessment (Allen et al., 2020). These advances were impressively showcased and discussed at the 4th European Hail Workshop in 2024.

However, our understanding of hail as both a meteorological phenomenon and a major societal hazard remains incomplete and marked by uncertainty. Recurring issues, needs, and perspectives highlighted across sessions include to following points:

- There is a great need for long-term, high-quality hail datasets that integrate radar, satellite, and ground-based measurements to improve climatologies and model validation. Crowd-sourced severe weather reports collected via weather apps (e.g., European Weather OBserver App EWOB; MeteoSwiss App; DWD App, Groenemeijer et al., 2017) offer great potential to fill the observational gap. However, additional information on hailstone shape and 3D structure is also desirable, as the commonly reported largest diameter (see Figure 2) often overestimates the potential impact of hailstones.
- To further advance hail hazard and risk estimation, reliable high-resolution hail climatologies combining radar and satellite proxies with ground-based observations are essential in regions where current information is limited. Such datasets would enable more accurate assessments of hail frequency, intensity, and spatial distribution, thereby

enhancing both scientific understanding and practical risk management.
- Studies on hail damage should also consider concurrent hazards such as wind-driven hail or hail with heavy rainfall, which often drive the most severe impacts but remain poorly characterized. Improved hail-damage and risk models additionally rely on high-resolution observational datasets with high spatial resolution and high temporal coverage.
- Both field campaigns and laboratory experiments can provide essential high-resolution data on processes relevant for hailstorm formation, hail growth, and impact-based modeling. Such datasets are essential for refinements of hail growth parameterizations, improved real-time hailstorm monitoring through advanced observational techniques, or reliable impact estimations for various exposed assets via improved vulnerability functions.
- Understanding climate change impacts on hail frequency and intensity requires deeper knowledge of the underlying processes that influence future hail occurrence and severity (e.g., CAPE, wind shear, freezing levels) and large-scale weather patterns (Raupach et al., 2021). Seamless coupling of kilometer-scale weather prediction and climate simulations is a promising approach for reconstructing past hail events and assessing future trends.
- ML/AI methods have proven powerful for developing hail risk models, damage assessments, and characterizing hail properties (McGovern et al., 2023). These approaches can be further leveraged to support future operational forecasting and to explore novel ways of characterizing compound events, paving the way for more targeted mitigation strategies.
- Finally, we strongly encourage cross-disciplinary collaboration among meteorological, engineering, and insurance communities to standardize methodologies and improve the translation of hazard data into actionable risk information. Hail hazard and risk assessments should be incorporated in the design of buildings and critical infrastructure, including highly vulnerable assets such as large photovoltaic parks and wind farms.

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References

Ackermann, L., Soderholm, J., Protat, A., Whitley, R., Ye, L., and Ridder, N. (2023). Radar and environment-based hail damage estimates using machine learning. *Atmos. Meas. Tech. Discuss.* 2023, 407–422. doi:10.5194/amt-17-407-2024

Adams-Selin, R. D. (2023). A three-dimensional hail trajectory clustering technique. *Mon. Weather Rev.* 151, 2361–2375. doi:10.1175/MWR-D-22-0345.1

Adams-Selin, R. (2025). The quasi-stochastic nature of hail growth: hail trajectory clusters in simulations of the Kingfisher, Oklahoma, hailstorm. *Mon. Weather Rev.* 153, 67–87. doi:10.1175/MWR-D-23-0233.1

Adams-Selin, R. D., and Ziegler, C. L. (2016). Forecasting hail using a one-dimensional hail growth model within wrf. *Mon. Weather Rev.* 144, 4919–4939. doi:10.1175/MWR-D-16-0027.1

Adams-Selin, R. D., Allen, J. T., Gensini, V. A., Heymsfield, A. J., Argrow, B. M., Giammanco, I. M., et al. (2024). "Introduction to the *in-situ* collaborative experiment for the collection of hail in the plains (icechip) campaign," in *31st conference on severe local storms* (Virginia Beach, VA: Amer. Meteor. Soc.).

Allen, J. T., Giammanco, I. M., Kumjian, M. R., Punge, H. J., Zhang, Q., Groenemeijer, P., et al. (2020). Understanding hail in the earth system. *Rev. Geophys.* 58, e2019RG000665. doi:10.1029/2019RG000665

Aregger, M., Martius, O., Germann, U., and Hering, A. (2025). Differential reflectivity columns and hail: linking C-band radar-based estimated column characteristics to crowdsourced hail observations in Switzerland. *Q. J. R. Meteorological Soc.* 151, e5003doi. doi:10.1002/qj.5003

Battaglioli, F., Groenemeijer, P., Púčik, T., Taszarek, M., Ulbrich, U., and Rust, H. (2023). Modeled multidecadal trends of lightning and (very) large hail in Europe and North America (1950–2021). *J. Appl. Meteorology Climatol.* 62, 1627–1653. doi:10.1175/JAMC-D-22-0195.1

Berman, M. T., Trapp, R. J., Nesbitt, S. W., and Di Girolamo, L. (2024). The observed impact of the lower stratospheric thermodynamic environment on overshooting top characteristics during the relampago-cacti field campaign. *J. Geophys. Res. Atmos.* 129, e2023JD040348. doi:10.1029/2023JD040348

Bernal Ayala, A. C., Rowe, A. K., Arena, L. E., Nachlas, W. O., and Asar, M. L. (2024). Exploring non-soluble particles in hailstones through innovative confocal laser and scanning electron microscopy techniques. *Atmos. Meas. Tech.* 17, 5561–5579. doi:10.5194/amt-17-5561-2024

Brennan, K. P., Sprenger, M., Walser, A., Arpagaus, M., and Wernli, H. (2025). An object-based and Lagrangian view on an intense hailstorm day in Switzerland as represented in COSMO-1E ensemble hindcast simulations. *Weather Clim. Dyn.* 6, 645–668. doi:10.5194/wcd-6-645-2025

Cui, R., Thurnherr, I., Velasquez, P., Brennan, K., Leclair, M., Mazzoleni, A., et al. (2025). A european hail and lightning climatology from an 11-year kilometer-scale regional climate simulation. *J. Geophys. Res. Atmos.* 130, e2024JD042828. doi:10.1029/2024JD042828

De Martin, F., Manzato, A., Carlon, N., Setvák, M., and Miglietta, M. M. (2025). Dynamic and statistical analysis of giant hail environments in northeast Italy. *Q. J. R. Meteorological Soc.* 151, e4945doi. doi:10.1002/qj.4945

Ehrensperger, G., Meyer, V. K., Falkensteiner, M.-A., and Hell, T. (2025). From radar to risk: building a high-resolution hail database for Austria and estimating risk through the integration of distributional neural networks into the metastatistical framework. *arXiv e-prints*. doi:10.48550/arXiv.2507.06429

Farnell Barqué, C., Rigo, T., Martin-Vide, J., and Úbeda, X. (2024). Internal structure of giant hail in a catastrophic event in Catalonia (NE Iberian Peninsula). *Front. Environ. Sci.* 12, 1479824. doi:10.3389/fenvs.2024.1479824

Feldmann, M., Domeisen, D. I., and Martius, O. (2025). A pan-European analysis of large-scale drivers of severe convective outbreaks. *EGUsphere* 2025, 1–24. doi:10.5194/egusphere-2025-2296

Ferrone, A., Kopp, J., Lainer, M., Gabella, M., Germann, U., and Berne, A. (2024). Double-moment normalization of hail size number distributions over Switzerland. *Atmos. Meas. Tech.* 17, 7143–7168. doi:10.5194/amt-17-7143-2024

Fischer, J., Kunz, M., Lombardo, K., and Kumjian, M. R. (2025). Hail trajectories in a wide spectrum of supercell-like updrafts. *J. Atmos. Sci.* 82, 1403–1422. doi:10.1175/JAS-D-24-0222.1

Galligani, V. S., Bang, S. D., Cancelada, M., Salio, P., Bechis, H., Mezher, R., et al. (2024). Testing a spaceborne passive-microwave severe hail retrieval over Argentina using ground-based dual-polarization radar data. *Q. J. R. Meteorological Soc.* 150, 5127–5145. doi:10.1002/qj.4861

Groenemeijer, P., Púčik, T., Holzer, A. M., Antonescu, B., Riemann-Campe, K., Schultz, D. M., et al. (2017). Severe convective storms in Europe: ten years of research and education at the European severe storms laboratory. *Bull. Am. Meteorological Soc.* 98, 2641–2651. doi:10.1175/BAMS-D-16-0067.1

Groot, E., Kuntze, P., Miltenberger, A., and Tost, H. (2024). Divergent convective outflow in icon deep-convection-permitting and parameterised deep convection simulations. *Weather Clim. Dyn.* 5, 779–803. doi:10.5194/wcd-5-779-2024

Kahraman, A., Kendon, E. J., and Fowler, H. J. (2024). Climatology of severe hail potential in Europe based on a convection-permitting simulation. *Clim. Dyn.* 62, 6625–6642. doi:10.1007/s00382-024-07227-w

Klaus, V., and Krause, J. (2024). Investigating hailstorm updrafts and nowcasting hail size using a novel radar-based updraft detection. *Weather Forecast.* 39, 1795–1815. doi:10.1175/WAF-D-23-0227.1

Kopp, J., Hering, A., Germann, U., and Martius, O. (2024). Verification of weather-radar-based hail metrics with crowdsourced observations from Switzerland. *Atmos. Meas. Tech.* 17, 4529–4552. doi:10.5194/amt-17-4529-2024

Lainer, M., Brennan, K. P., Hering, A., Kopp, J., Monhart, S., Wolfensberger, D., et al. (2023). Drone-based photogrammetry combined with deep-learning to estimate hail size distributions and melting of hail on the ground. *Atmos. Meas. Tech. Discuss.* 2023, 2539–2557. doi:10.5194/amt-17-2539-2024

Lasher-Trapp, S., Orendorf, S. A., and Trapp, R. J. (2023). Investigating a derecho in a future warmer climate. *Bull. Am. Meteorological Soc.* 104, E1831–E1852. doi:10.1175/bams-d-22-0173.1

Le, M., and Chandrasekar, V. (2023). Hail identification algorithm for dpr onboard the gpm satellite. *IEEE Trans. Geoscience Remote Sens.* 61, 1–14. doi:10.1109/TGRS.2023.3320972

Lin, Y., and Kumjian, M. R. (2022). Influences of cape on hail production in simulated supercell storms. *J. Atmos. Sci.* 79, 179–204. doi:10.1175/JAS-D-21-0054.1

Lin, Y., Kumjian, M. R., Soderholm, J., and Giammanco, I. (2024). Modeling nonspherical hailstones. *J. Atmos. Sci.* 81, 1849–1881. doi:10.1175/JAS-D-23-0231.1

Lin, X., Zhang, H., Li, X., Zhang, Q., Heymsfield, A., Bi, K., et al. (2025). Isotopic analysis for tracing vertical growth trajectories of hailstones. *Adv. Atmos. Sci.* 42, 1195–1211. doi:10.1007/s00376-024-4211-x

Ma, R., and Li, X. (2024). Effects of a vertical cloud condensation nuclei concentration explosion in an idealized hailstorm simulation. *Geophys. Res. Lett.* 51, e2024GL108592. doi:10.1029/2024GL108592

Mallinson, H., Lasher-Trapp, S., Trapp, J., Woods, M., and Orendorf, S. (2024). Hailfall in a possible future climate using a pseudo–global warming approach: hail characteristics and mesoscale influences. *J. Clim.* 37, 527–549. doi:10.1175/JCLI-D-23-0181.1

Manzato, A., Cicogna, A., Centore, M., Battistutta, P., and Trevisan, M. (2022). Hailstone characteristics in northeast Italy from 29 years of hailpad data. *J. Appl. Meteorology Climatol.* 61, 1779–1795. doi:10.1175/JAMC-D-21-0251.1

Manzato, A., Fasano, G., Cicogna, A., Sioni, F., and Pucillo, A. (2025). Relationships between environmental parameters and storm observations in Po Valley: are they climate change invariant? *J. Appl. Meteorology Climatol.* 64, 267–298. doi:10.1175/JAMC-D-24-0034.1

McGovern, A., Chase, R. J., Flora, M., Gagne, D. J., Lagerquist, R., Potvin, C. K., et al. (2023). A review of machine learning for convective weather. *Artif. Intell. Earth Syst.* 2, e220077. doi:10.1175/AIES-D-22-0077.1

Meisenzahl, B., Giammanco, I., and Hedayati, F. (2025). Sub-severe hail: the missing piece in assessing asphalt shingle risk in North America. *Front. Mater.* 12, 1603074. doi:10.3389/fmats.2025.1603074

Mohamed, I., Najafi, M. R., Joe, P., and Brimelow, J. (2024). Multivariate analysis of compound hail, wind and rainfall extremes in alberta's hail alley. *Weather Clim. Extrem.* 46, 100718. doi:10.1016/j.wace.2024.100718

Portmann, R., Schmid, T., Villiger, L., Bresch, D. N., and Calanca, P. (2024). Modelling crop hail damage footprints with single-polarization radar: the roles of spatial resolution, hail intensity, and cropland density. *Nat. Hazards Earth Syst. Sci.* 24, 2541–2558. doi:10.5194/nhess-24-2541-2024

Portmann, J., Lainer, M., Brennan, K. P., Jourdain de Thieulloy, M., Guidicelli, M., and Monhart, S. (2025). Performance assessment of drone-based photogrammetry coupled with machine-learning for the estimation of hail size distributions on the ground. *Front. Environ. Sci.* 13, 1602917. doi:10.3389/fenvs.2025.1602917

Raupach, T. H., Martius, O., Allen, J. T., Kunz, M., Lasher-Trapp, S., Mohr, S., et al. (2021). The effects of climate change on hailstorms. *Nat. Rev. earth and Environ.* 2, 213–226. doi:10.1038/s43017-020-00133-9

Scarino, B., Itterly, K., Bedka, K., Homeyer, C. R., Allen, J., Bang, S., et al. (2023). Deriving severe hail likelihood from satellite observations and model reanalysis parameters using a deep neural network. *Artif. Intell. Earth Syst.* 2, 220042. doi:10.1175/AIES-D-22-0042.1

Schmid, T., Portmann, R., Villiger, L., Schröer, K., and Bresch, D. N. (2024). An open-source radar-based hail damage model for buildings and cars. *Nat. Hazards Earth Syst. Sci.* 24, 847–872. doi:10.5194/nhess-24-847-2024

Schmid, T., Gebhart, V., and Bresch, D. N. (2025). Improved real-time hail damage estimates leveraging dense crowdsourced observations. *Meteorol. Appl.* 32, e70059. doi:10.1002/met.70059

Schmidt, T. G., McGovern, A., Allen, J. T., Potvin, C. K., Chase, R. J., Wiley, C. M., et al. (2024). Gridded severe hail nowcasting using 3d u-nets, lightning observations, and the warn-on-forecast system. *Artif. Intell. Earth Syst.* 3, 240026. doi:10.1175/AIES-D-24-0026.1

Seidel, J. S., Kiselev, A. A., Keinert, A., Stratmann, F., Leisner, T., and Hartmann, S. (2024). Secondary ice production–no evidence of efficient rime-splintering mechanism. *Atmos. Chem. Phys.* 24, 5247–5263. doi:10.5194/acp-24-5247-2024

Soderholm, J. S., Kumjian, M. R., Brook, J. P., Peterson, A., Protat, A., Brimelow, J., et al. (2025). Measuring hail-like trajectories and growth with the hailsonde. *Bull. Am. Meteorological Soc.* 106, E2128–E2142. doi:10.1175/BAMS-D-24-0021.1

SwissRe (2024). *Sigma 01/2024: natural catastrophes in 2023: gearing up for today's and tomorrow's weather risks*. Zurich, Switzerland: Swiss Re Institute. Available online at: https://www.swissre.com/institute/research/sigma-research/sigma-2024-01.html (Accessed April 28, 2025).

Theis, A., Szakáll, M., Diehl, K., Mitra, S. K., Zanger, F., Heymsfield, A., et al. (2022). Vertical wind tunnel experiments and a theoretical study on the microphysics of melting low-density graupel. *J. Atmos. Sci.* 79, 1069–1087. doi:10.1175/JAS-D-21-0162.1

Theis, A., Voll, L., Diehl, K., Heymsfield, A., Giammanco, I., Borrmann, S., et al. (2025). A wind tunnel investigation into the aerodynamics of natural hailstones. *J. Atmos. Sci.* doi:10.1175/JAS-D-25-0015.1

Thurnherr, I., Cui, R., Velasquez, P., Wernli, H., and Schär, C. (2025). The effect of 3° ${}{\circ}$C global warming on hail over Europe. *Geophys. Res. Lett.* 52, e2025GL114811. doi:10.1029/2025gl114811

Tonn, M., Barthlott, C., Kunz, M., and Hoose, C. (2025). Impact of wind shear on aerosol-cloud interactions and convective precipitation. *Front. Environ. Sci.* 13, 1566365. doi:10.3389/fenvs.2025.1566365

Vagasky, H. C., Adams-Selin, R. D., Bang, S. D., Heymsfield, A. J., and Bansemer, A. (2025). The sensitivity of falling hail to different melting and terminal velocity parameterizations and environmental conditions. *Mon. Weather Rev.* 153, 2535–2554. doi:10.1175/MWR-D-24-0180.1

Wells, H. M., Hillier, J., Garry, F. K., Dunstone, N., Clark, M. R., Kahraman, A., et al. (2024). Climatology and convective mode of severe hail in the United Kingdom. *Atmos. Res.* 309, 107569. doi:10.1016/j.atmosres.2024.107569

Wilhelm, L., Schwierz, C., Schröer, K., Taszarek, M., and Martius, O. (2024). Reconstructing hail days in Switzerland with statistical models (1959–2022). *Nat. Hazards Earth Syst. Sci.* 24, 3869–3894. doi:10.5194/nhess-24-3869-2024