BAMS In Box

Insights from a European Hail Research Project—A Seamless Approach from Observations and Numerical Simulations to Impacts in a Changing Climate

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ABSTRACT: Severe convective storms were the costliest natural hazard globally in 2023, with hail as a major driver of economic losses. Single hail events regularly cause damage exceeding 4 billion U.S. dollars in Europe (e.g., France 2022, Italy 2023). The substantial risk of hail prompted the research initiative *scClim* in Switzerland, which unites expertise from multiple disciplines to advance the understanding of hail risk and its impacts in a changing climate across central Europe. Our approach combines a unique set of hail observations from high-resolution polarimetric radars, automated surface-based sensors, drones, and crowdsourced reports with European-wide convection-permitting climate simulations featuring an online hail diagnostic (HAILCAST). We further developed an open-source, seamless hail impact modeling platform together with stakeholders. The platform provides hail event hindcasts, forecasts, and impact assessments for vehicles, buildings, and crops, using the CLIMADA risk modeling framework. Our climate simulations, generating 11-yr hail climatologies for both the present climate and a +3°C warming scenario, show increased hail frequencies in northeastern Europe and decreased frequencies in southwestern Europe. Hailstorm track analyses reveal larger maximum hail sizes, more extensive hail swaths, and intensified precipitation and wind for cells producing large hail. Consequently, the future hail damage potential to buildings increases, while agricultural impacts present a more complex picture: Earlier growing seasons reduce crop exposure to hail, but regional increases in hail frequency amplify overall risk. These findings provide novel insights for developing adaptation strategies in sectors vulnerable to hail damage in a warming climate.

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1. Introduction

Among all severe convective storm (SCS)-related perils, hail is the most damaging in terms of insured losses, with individual events regularly inflicting losses in the billions (U.S. dollars), as seen recently in the Twin Cities (United States, 2023), Calgary (Canada, 2024), and Kansai (Japan, 2024). Europe, in particular, has experienced a surge in high-impact hailstorms: A series of severe storms caused widespread damage across central Europe in 2021 (SwissRe 2021), including record-breaking hail losses in Switzerland. The following year, France also reported record hail losses (Assureurs 2023; SwissRe 2023), followed by northern Italy in 2023, where a 19-cm hailstone set a new European hail size record [European Severe Storms Laboratory (ESSL) 2023]. These events highlight the substantial risk posed by hailstorms, which government agencies, industry, and the public must manage to strengthen societal resilience.

Switzerland is one of Europe's hail hotspots, where hail consistently ranks as the leading cause of losses in both property and agricultural insurance records (Schadensstatistik VKG 2025; Schweizer Hagel 2025). Consequently, decision-makers require actionable information to address the socioeconomic impacts of hailstorms across multiple time scales, from short-term warnings and risk assessments to long-term strategic planning under a changing climate. Developing such decision-support tools, however, presents several major challenges. Hail exhibits high spatial and temporal variability, making it inherently difficult to observe. Furthermore, it is not explicitly resolved in operational weather prediction and climate models. Its socioeconomic impacts span multiple sectors, from agriculture to infrastructure, each with distinct exposure patterns and vulnerabilities. Uncertainties about how hail frequency and intensity will change in a warmer climate (e.g., Martius et al. 2018; Allen et al. 2020; Raupach et al. 2021; Kahraman et al. 2025) further complicate risk assessment and communication.

To address these challenges, the research initiative *scClim* (Seamless coupling of kilometer-resolution weather predictions and climate simulations with hail impact assessments for multiple sectors; see https://scclim.ethz.ch/) was launched in 2022 in Switzerland. The project integrated advances in hail observations, state-of-the-art convection-permitting numerical weather prediction model simulations including the HAILCAST diagnostic (Adams-Selin and Ziegler 2016), sector-specific impact modeling, and stakeholder dialogue to advance the understanding of hail and its impacts in Europe, both now and under a warming climate. The core innovations and outcomes of *scClim* are

1) The production of several new observational hail datasets (section 2; Wilhelm et al. 2024; Schmid et al. 2025; Aregger et al. 2025; Cui et al. 2025).

2) The development of a probabilistic model chain that combines high-resolution numerical weather prediction, radar, and surface-based hail observations with impact modeling to assess hail risk for agriculture, infrastructure, and vehicles across multiple time scales (section 3; Schmid et al. 2024; Portmann et al. 2024; Schmid et al. 2025).
3) The codevelopment of an operational online demonstrator of the model chain with and for stakeholders, supporting the development of impact-based hail warnings (section 3).
4) The assessment of future hail risk under climate change, using convection-permitting pseudo–global warming simulations to quantify changes in hail frequency, intensity, environments, and related impacts in Switzerland and across Europe (section 4; Thurnherr et al. 2025; Brennan et al. 2025b).

In this article, we aim to highlight key results from this 4-yr project, starting with the diverse observational datasets that made these advances possible.

2. The value of diverse hail observation datasets

Switzerland's vulnerability to hail damage has long motivated research, beginning with hail suppression experiments after the Second World War (e.g., Hagelgrossversuch I–IV), and fundamental research into hail physics, including radar backscattering, melting, and wind tunnel experiments (e.g., Joss 1964; Federer et al. 1986; Auf Der Maur and Germann 2021). In the 2000s, the first radar-based single-polarization hail detection products were implemented on the Swiss weather radar network: the probability of hail (POH; Waldvogel et al. 1979; Foote et al. 2005) and the hail-sizing algorithm maximum expected severe hail size (MESHS; Treloar 1998; Joe et al. 2004). More recently (2011–16), the dense C-band radar network was upgraded to dual polarization, which opened new possibilities in hail observation, including hydrometeor classification (Germann et al. 2022; Besic et al. 2016, 2018). These radar advancements were complemented by innovative surface-based hail observations. In 2015, a unique network of automated digital hail sensors was deployed in Switzerland's hail hotspots (Fig. 1; Loeffler-Mang et al. 2011; Kopp et al. 2023a; Ferrone et al. 2024), and a real-time hail reporting function was implemented in the MeteoSwiss weather app in May 2015 (Barras et al. 2019; Kopp et al. 2023b). The function has since been widely adopted by the users, resulting in a uniquely large crowdsourced hail size report dataset (CRD), containing over 400 000 submitted reports over the last 10 years (Fig. 1). The latest addition to this suite of observations is a set of hail-size-distribution measurements derived from drone-based photogrammetry (Lainer et al. 2024; J. Portmann et al. 2025).

This wealth of observational data provided fertile ground for research within *scClim*.

Using the CRD, Schmid et al. (2025) developed a filtered and gridded, now publicly available hail size dataset for Switzerland (Schmid 2025), which in turn allowed for improved hail damage models for vehicles and buildings (Schmid et al. 2025) (see section 3), thereby enhancing the accuracy of postevent impact assessments. The CRD also facilitated the development of a new generation of

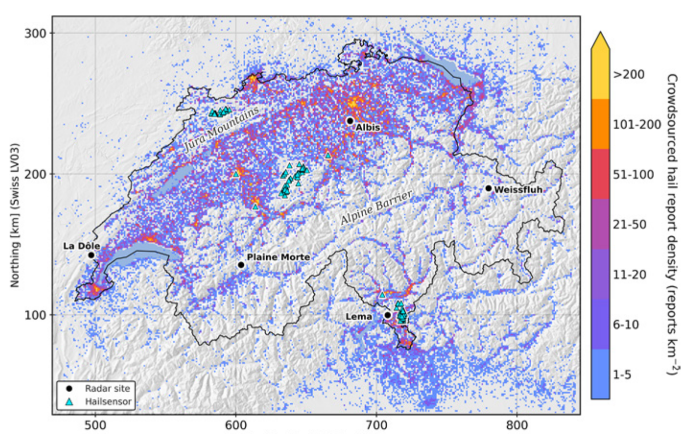

Fig. 1. Spatial distribution of crowdsourced hail reports in Switzerland (complete dataset since 2015). The color scale indicates the density of reports per square kilometer. The locations of the MeteoSwiss weather radar sites (black circles) and automated hail sensors (cyan triangles) are also shown.

radar-based Swiss hail-sizing algorithms. For example, Aregger et al. (2026) used it to train a new machine learning–based hail-sizing algorithm using polarimetric data, which outperforms the operational MESHS and POH.

Last, we highlight the development of *EURADHAIL* (Cui and Thurnherr 2024), a new open-source, high-resolution pan-European hail occurrence dataset derived from the European OPERA radar composite (Huuskonen et al. 2014), POH, lightning, and precipitation data. *EURADHAIL* provides binary information on hail occurrence at 2-km spatial and hourly temporal resolution for the period 2013–21, offering a novel observational basis for climatological analyses of hail occurrence and model validation (Cui et al. 2025). The dataset has already enabled new insights, including the identification of a significant statistical link between elevated Saharan dust concentrations and increased hail occurrence in Europe (Brennan and Wilhelm 2025).

Our diverse suite of observations enabled progress in hail research that would have been impossible with any single method. While automated sensors and drones provide high precision, radar offers long-term stability and broad coverage, and citizen science fills observational gaps by supplying extensive data about hail occurrence and size at low cost. Combining these sources can create the extensive training and validation datasets essential for modern machine learning applications in meteorology, while also offering novel insights into the impacts of hailstorms. Together, they form the empirical foundation for *scClim's* model chain, as discussed in the following section.

3. From hazard to impact: An open-source model chain codeveloped with stakeholders

At the heart of *scClim* lies a model chain that seamlessly translates hail estimates into sector-specific impact assessments. More than just a conceptual tool, it represents an interdisciplinary effort to advance both science and practice, built through continuous exchange with stakeholders to align research with real-world needs. The model framework is schematically illustrated in Fig. 2. The chain begins by quantifying the hail hazard. For postevent analysis, it draws on the radar and crowdsourced datasets described previously. For forecasts, it utilizes hail size output from the MeteoSwiss numerical weather prediction (NWP) ensemble coupled with the HAILCAST diagnostic (Brimelow et al. 2002; Adams-Selin and Ziegler 2016).

The hazard data feed into exposure-specific risk models, developed using the open-source risk assessment platform CLIMADA (Aznar-Siguan and Bresch 2019). Impact functions were calibrated for vehicles, buildings, and major crops using granular insurance loss and exposure data provided by project partners, namely, building and agricultural insurers

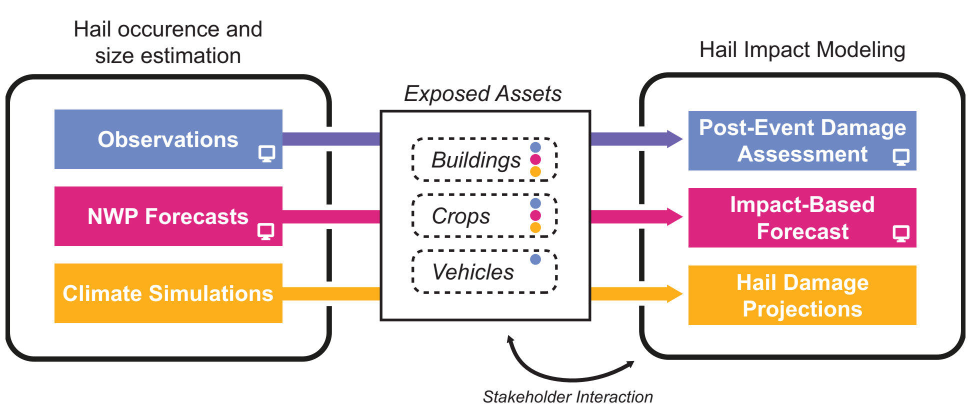

Fig. 2. Schematic of the model chain with its core elements. The white computer icons signify that these elements are part of the online demonstrator. The colored dots indicate which modeling chain has been applied for the respective asset.

(Schmid et al. 2024; Portmann et al. 2024; Schmid et al. 2025). These functions map hazard intensity to impact, such as monetary damage (for vehicles and buildings) or the number of assets affected (for vehicles, buildings, and crops). For pre-event applications (i.e., impact forecasts), the hail hazard is derived from the NWP ensemble and coupled with exposure distributions for the different sectors, thereby transforming weather forecasts into tangible damage predictions. For postevent impact assessments, the hail hazard is derived from observational data [radar, crowdsourced dataset (CRD)] (Portmann et al. 2024; Schmid et al. 2024, 2025).

To ensure these products are interpretable and relevant to their users, stakeholder engagement was a central component of *scClim's* design. The project strongly benefited from a transdisciplinary collaboration approach (Fischer et al. 2021), involving nearly a dozen stakeholders (e.g., insurance, reinsurances, first responders, MeteoSwiss) from the proposal stage onward and maintaining active engagement throughout the 4-yr period. This was achieved through regular meetings, workshops, and the development of an online demonstrator (Fig. 3), an interactive platform that allowed users to explore hail hazard observations, nowcasts (Leinonen et al. 2023), forecasts, and damage estimates produced by *scClim* (accessible at https://data.iac.ethz.ch/WCR_sandbox/HaSchaWa_V2/, Schmid et al. 2026a).

The close collaboration with stakeholders, structured as a mutually beneficial exchange, proved highly effective. For instance, insurance partners provided detailed loss and exposure data early on, enabling rapid calibration of our impact functions. In return, the project delivered state-of-the-art hazard data and impact models applicable to the partners' portfolios,

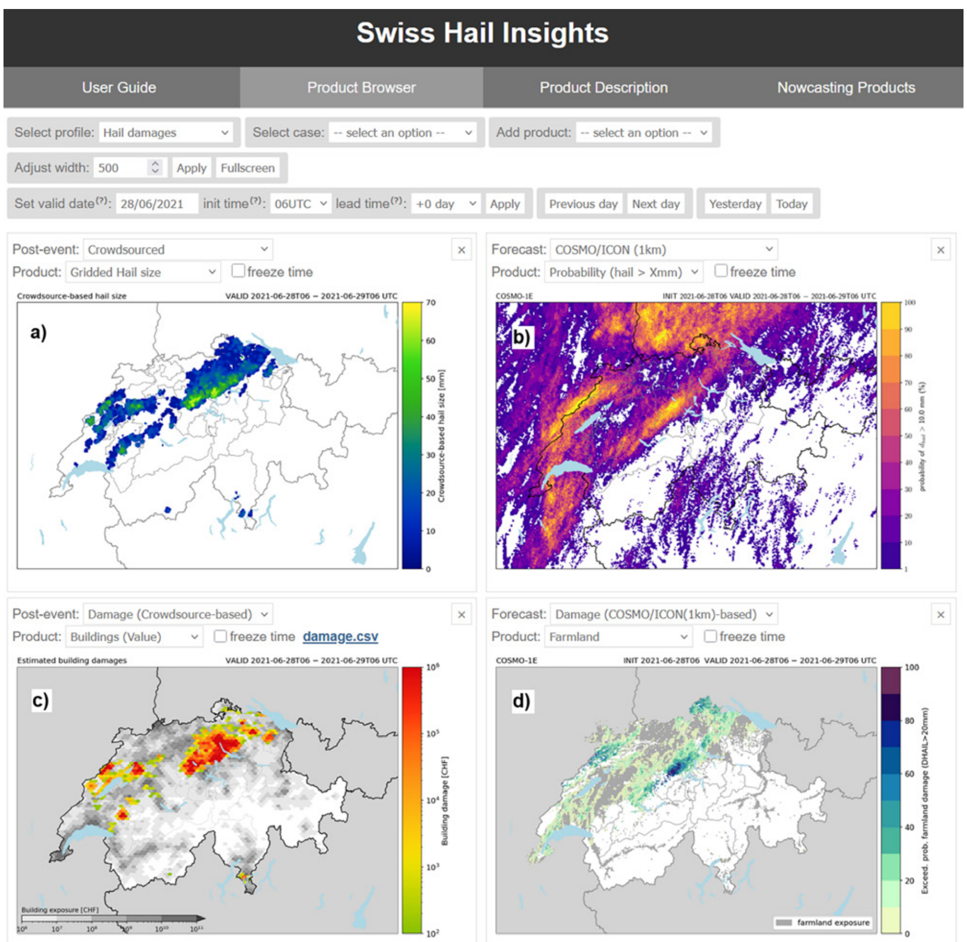

Fig. 3. **A screenshot of the online demonstrator with a selection of available products displayed for 28 Jun 2021. (a) Gridded crowdsourced hail size, (b) NWP probability of hail with a diameter > 10 mm, (c) postevent building damage estimation based on the gridded crowdsource product, and (d) pre-event damage-probability forecast for farmland.**

along with new insights into hail risk and its potential future evolution, directly supporting risk assessment and business decisions.

Further, stakeholders continuously evaluated the results displayed in the online demonstrator and provided feedback on its usefulness, allowing for iterative improvement. Finally, the continuous exchange revealed diverse stakeholder needs: First responders value short-term warnings about hail occurrence, while building insurance providers prioritize highly resolved, rapidly available postevent damage estimates. In contrast, reinsurers found long-term trends in hail frequency and intensity to be most relevant. These differing perspectives underscore the value of *scClim's* codevelopment approach, which ensured that scientific advances were closely aligned with end-user requirements.

The final application of the modeling chain extends beyond short-term forecasting. In the following section, we apply the same approach to climate simulations to assess how hail risk and its impacts may evolve under future warming.

4. Hail risk in a warming climate

The *scClim* project examined the influence of global warming on hailstorms using two complementary approaches: assessing past trends using long-term reconstructed hail observations and exploring potential future changes through convection-permitting climate simulations.

Wilhelm et al. (2024) showed that the hail hazard has already evolved in the past. For Switzerland, a newly reconstructed hail day occurrence dataset revealed a significant 10% increase in yearly hail days per decade between 1959 and 2022, which is driven by trends in instability and moisture predictors.

To assess how such trends may continue under future warming, *scClim* ran decade-long, convection-permitting climate simulations for Europe with HAILCAST for a present-day climate (2011–21, CTRL) and a future +3°C climate, using the pseudo–global warming approach (PGW) (Brogli et al. 2023). The CTRL simulations have been extensively validated (Cui et al. 2025), and the effect of a warmer climate on hail occurrence has been analyzed by Thurnherr et al. (2025) and Brennan et al. (2025b).

Comparing CTRL to PGW simulations shows that in summer, the frequency of hail days with diameters exceeding 12.5 mm is projected to increase across northeastern and central Europe, particularly the Alpine region and the Po Valley, while decreases are projected over southwestern Europe (Fig. 4b). In contrast, small hail (<12.5 mm) occurrence is projected to decline across most of Europe. These changes are primarily linked to changes in CAPE and convective inhibition (CIN), driven by altered moisture availability in the lower troposphere. For smaller hail, elevated melting-level heights under warmer conditions will likely contribute to the projected decline (Thurnherr et al. 2025).

Overall, hailstorms become more severe in a warmer climate, regardless of frequency changes (Brennan et al. 2025b). Applying a storm-tracking algorithm (Brennan et al. 2025a), Brennan et al. (2025b) identified 40 000 hailstorm tracks in both climate periods. The number of storms producing hail larger than 50 mm nearly doubles, and hail swath areas increase on average by 15%–30%, resulting in broader spatial footprints. Maximum hail diameters increase in most regions, except parts of the Pyrenees (Fig. 4c). Associated hazards also intensify: Hailstorm-related precipitation increases by approximately 20% and wind extremes by 5%. Compound events, such as hail > 30 mm accompanied by rainfall > 50 mm h^{-1}, are projected to become twice as frequent (Brennan et al. 2025b).

To link these changes in hail frequency and intensity to impacts, we applied our impact models for buildings and crops from the modeling chain (see section 3) to the climate simulation output. Building damage potential increases across most of Europe, with an average rise of 25%–42%, though with large local sampling uncertainty. Decreases occur mainly over France and the Iberian Peninsula, consistent with projected hail frequency declines

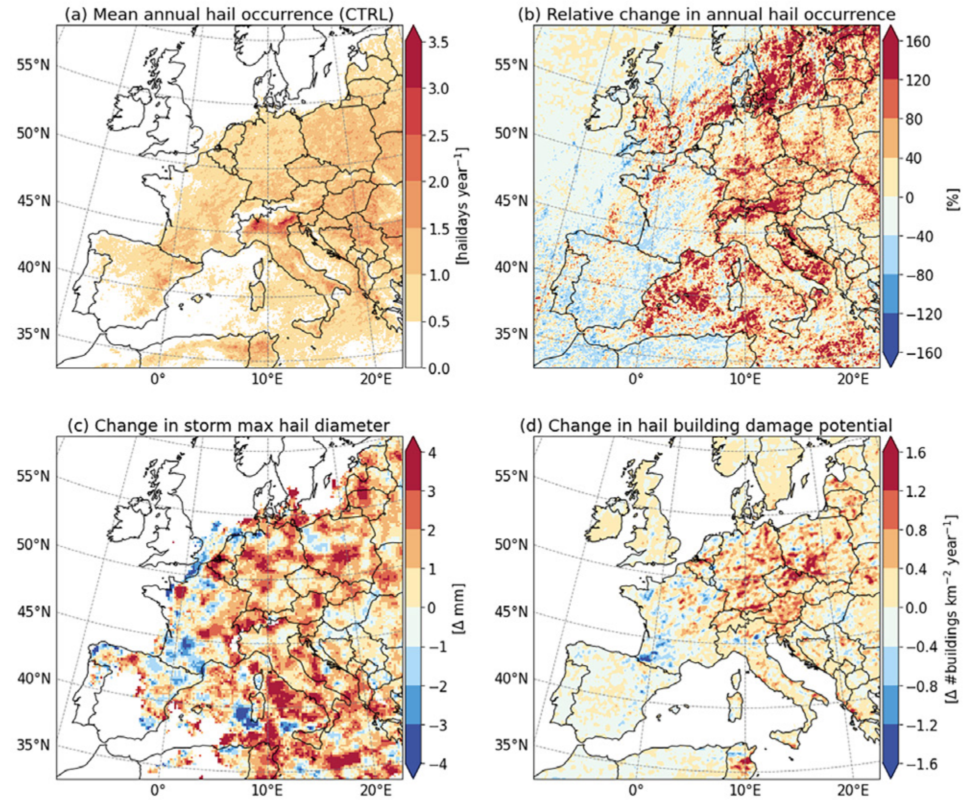

Fig. 4. Figure highlighting results from the *scClim* climate simulations: (a) mean annual climatology of hail days > 12.5 mm (CTRL) and (b) relative change in percentage from CTRL to PGW. (c) Mean annual change in the maximum hail diameter from tracked storms. Values are shown only at grid points with more than three storms. (d) Change in the hail damage potential, quantifying the expected number of damaged buildings per square kilometer per year assuming average building density. The changes in (c) and (d) represent absolute changes (PGW − CTRL), while (b) shows the changes in the PGW simulation relative to the CTRL simulation [(PGW − CTRL)/CTRL]. Plots (a) and (b) are adapted from Thurnherr et al. (2025), (c) adapted from Brennan et al. (2025b), and (d) adapted from Schmid et al. (2026b).

(Figs. 4a,d) (Schmid et al. 2026b). For agriculture, projected shifts toward earlier crop phenology shorten hail exposure windows (R. Portmann et al. 2025), but this benefit is offset by more frequent hail in central and northeastern Europe. In contrast, southwestern Europe, including the Iberian Peninsula, is expected to see lower crop hail risk.

Our results demonstrate that we can only capture the complexity of future hail risk with an integrated approach considering changes in the hazard, combined with evolving exposure and potential changes in vulnerability.

5. Conclusions and future directions

Over 4 years, *scClim* brought together research institutions, insurers, and public agencies to develop an integrated framework for understanding and managing hail risk. This effort was driven by a core research team consisting of four principal investigators, four PhD students, three postdoctoral researchers, and one scientific staff and was further strengthened by contributions from numerous students and collaborating stakeholders (for a comprehensive list, see https://scclim.ethz.ch/people). The project combined new hail observation networks, open-source impact modeling, high-resolution climate simulations, and a real-time online demonstrator codeveloped with stakeholders. Together, these elements advanced both the science of hail and the translation of that science into tools for decision-makers. The open-source datasets, impact functions, and interactive platform provide a practical foundation for issuing impact-based warnings and conducting long-term risk assessments in a changing climate. Climate simulations from *scClim* have already been utilized outside of the project in a first-of-its-kind European-wide study of supercell occurrence in a warming climate (Feldmann et al. 2025).

While the project focused on hail in Switzerland and Europe, its methods are widely transferable. The seamless hazard-to-impact model chain, developed within the open-source CLIMADA framework, can be applied to other convective hazards such as wind, flash floods, or compound events and to different regions. In this sense, *scClim* served as a prototype for interdisciplinary, user-oriented climate-risk research.

Substantial challenges remain. From a modeling perspective, the climate simulations rely on a single model setup, one-moment microphysics scheme, and one pseudo–global warming scenario. Approaches such as multimodel ensembles and more advanced microphysics schemes (e.g., Jensen et al. 2023; Milbrandt et al. 2025) have the potential to better quantify uncertainty in hail forecasts, especially for larger hail sizes that HAILCAST has been shown to underestimate (Adams-Selin et al. 2019; Cui et al. 2025). On the impact side, current vulnerability functions typically reproduce only the correct order of magnitude. Improving these functions will require more detailed and component-resolved loss data. Such information could be obtained through comprehensive postevent surveys and through more detailed insurance data, including information on property characteristics and elemental repair costs. Detailed vulnerability studies should be a key priority for future research to improve the robustness of hail damage estimates. Similarly, observations of the size and spatial distribution of hail need to be extended to capture event intensity, hail size distribution, timing, and location more accurately. Promising approaches include drone-based measurements, systematic analysis of crowdsourced images via image recognition, and the use of webcams or social media. Looking forward, assimilating these novel observations into nowcasting systems such as AI-DOP (McNally et al. 2024) or machine learning–enhanced frameworks like COALITION4 (Leinonen et al. 2023) could further improve hail nowcasting, though careful validation and operational testing are required. Finally, open questions remain regarding how aerosols and atmospheric dust influence hail formation in Europe, and further research is needed to clarify causal mechanisms and to explore the role of aerosol type and trends in aerosol loading.

scClim demonstrated that sustained collaboration between scientists and end users shortens the path from research to application: Early engagement shaped useful products, rapid feedback improved model calibration, and operational partners helped define priorities. Extending this codevelopment approach while addressing the scientific and data challenges outlined above offers a practical pathway to strengthen preparedness and adaptation to hail and related hazards.

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