BAMS Article

Making Warnings Count: 10 Years of Research in High-Impact Weather

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ABSTRACT: The World Meteorological Organization (WMO) World Weather Research Programme (WWRP) High-Impact Weather (HIWeather) research project was designed to increase the effectiveness of forecasts and warnings of high-impact weather. In achieving this, it created a global momentum toward a growing partnership between the social and physical sciences in the weather enterprise, building a community of researchers and practitioners who understand the importance of working across disciplines and are passionate about the value of warnings in reducing the impact of weather-related hazards. Through its promotion of "Warning Chain Thinking" within the Warning Value Cycle, it focused attention on the whole warning system, from monitoring and forecasting through communication and response, emphasizing the role of partnerships among disciplines, organizations, decision-makers, and the public. It brought together a wide body of research from multiple disciplines involved in making warnings more effective, in a series of publications which are increasingly used in education, training, and operations. In doing so, it helped bridge gaps between weather information providers, emergency managers, and humanitarian organizations on a global scale. It has provided a community and a body of evidence as a foundation for the United Nations Early Warnings for All initiative and for the next generation of warnings research.

SIGNIFICANCE STATEMENT: The article highlights the importance of considering the high-impact weather forecasting and warning chain as an integrated whole, involving a range of actors from different organizations and disciplines. Three strands of science motivated this work: the need for progress in translating weather hazards into impacts; evidence to underpin the appropriate introduction of impact-based forecasts and warnings; and addressing the gap between the science of community response, espoused by humanitarian organizations, and the science of weather information production, exemplified by national weather services.

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Ebert: Retired.
Johnston: Deceased.

1. Context

As the world warms, weather patterns are changing, and extremes are occurring outside people's experience. At the same time, an increasing, more urbanized world population is resulting in more people, especially the most vulnerable, living in areas exposed to weather-related hazards. The Centre for the Epidemiology of Disasters (CRED 2025) observed that 2024 was the first year in which global temperatures exceeded 1.5°C above preindustrial level and that, despite advances in forecasting, communication, and civil protection, weather-related disasters:

- Claimed 16 000 lives: 5883 from floods, 5247 from extreme temperatures, 2582 from storms, 2243 from landslides, and 170 from wildfires.
- Affected 166 million people: 49 million by floods, 48 million by storms, 36 million by extreme temperatures, and 30 million by drought.
- Caused $230 billion (U.S. dollars) in damages: $175 billion (U.S. dollars) from storms, $34 billion (U.S. dollars) from floods, $13 billion (U.S. dollars) from drought, and $5 billion (U.S. dollars) from wildfires.

Infrastructure built for yesterday's climates is no longer adequate, but replacing or upgrading is costly, disruptive, and takes time. Warnings offer a quick, affordable, effective, and proven adaptation measure. They raise awareness and encourage protective action, enable timely preparation and response, and build trust.

The World Meteorological Organization (WMO)/World Weather Research Programme (WWRP) High-Impact Weather (HIWeather) project set out to grow understanding of how to design effective warning systems that save lives, reduce damage, and protect livelihoods. While the Sendai Framework (United Nations Office for Disaster Risk Reduction 2015) called for broader access to early warnings, HIWeather focused on what makes warnings effective, laying the foundation for the United Nations Early Warnings for All (EW4All; WMO 2022) initiative and supporting the goal of turning early warning into protective action.

2. The project

HIWeather was launched in 2015 by the WWRP as one of three successors to the THORPEX project (Parsons et al. 2017) to "Promote cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for time scales of minutes to 2 weeks and enhancing their communication and utility in social, economic and environmental applications" (WMO 2014). It built on THORPEX successes in increasing predictive skill while addressing the downstream part of the warning process, with research into risk and its communication that had made less progress in THORPEX. HIWeather focused on five hazard groups: floods, wildfires, extreme wind (including within tropical and extratropical cyclones and severe convection), disruptive winter weather (including solid and mixed precipitation, ice, and fog), and heat waves and air pollution (taken together due to their impacts on health). In the event, much of the work was agnostic to the hazard, while the partnerships with field experiments (see Table 3) determined the focus of much of the prediction work.

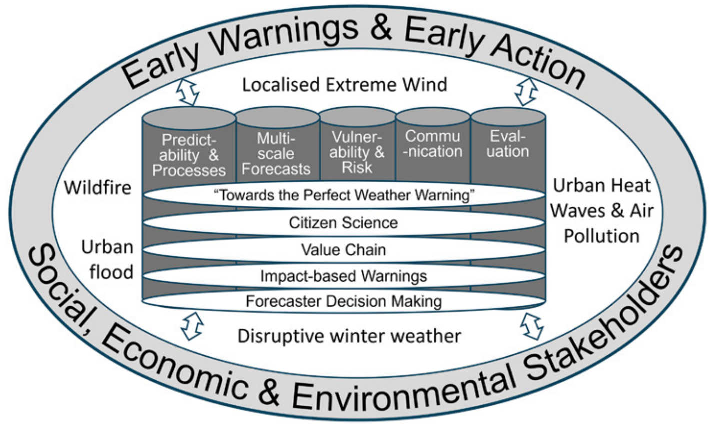

Fig. 1. Structure of the HIWeather project.

HIWeather involved 136 scientists, with the majority from Europe (50), North America (35), and Australasia (27). It was led by two cochairs—one representing physical sciences and one representing social sciences. An International Coordination Office in Beijing organized meetings and communications.

Work was structured around five disciplinary pillars which fed into five cross-cutting projects (Fig. 1). Each of these 10 activities was carried out by a task team with coordination and oversight from a Steering Committee consisting of activity chairs together with the HIWeather cochairs and the chief of WWRP in the WMO Secretariat. Due to the highly diverse nature of these activities, their methods of working and their engagement with external bodies were very different:

Predictability and processes research was carried out in close collaboration with a major research project, Waves to Weather (W2W), funded by the German Research Foundation [Deutsche Forschungsgemeinschaft (DFG)] which was a lead organizer of the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) field experiment and subsequent campaigns (Craig et al. 2021).

The multiscale forecasts team was lead from NCAR and collaborated widely with academic institutions and national weather services engaged in modeling and field experiments, especially in the United States and China. It also worked with WWRP working groups on data assimilation (DAOS), nowcasting (WGNMR), and predictability, dynamics, and ensemble forecasting (PDEF) on convective-scale hazard prediction.

Impacts, vulnerability, and risk research was led from Canada and the United Kingdom and involved numerous academic partners across engineering, epidemiology, economics, and other disciplines. Two key partner projects emerged: Tomorrow's Cities, funded by the UK Global Challenges Research Fund, focused on avoiding risk creation using scenario-based impact modeling (https://tomorrowscities.org/); and the EU-funded Human-Technology Nexus (HuT), connecting risk-reduction efforts in several countries to enhance impact modeling and risk reduction (https://thehut-nexus.eu/). Compound hazards were addressed through links with COST DAMOCLES (https://www.damocles.compoundevents.org/) and by establishing a strategic partnership with the Risk-Knowledge Action Network (Risk-KAN; https://www.risk-kan.org/).

Communications research was contributed by several academic groups, mainly in New Zealand, Germany, United Kingdom, Switzerland, and Australia, and in partnership with the WWRP Working Group on Societal and Economic Research Applications (WGSERA; see Göber et al. 2023).

The evaluation component was led from the Bureau of Meteorology in Australia in partnership with the WWRP Joint Working Group on Forecast Verification Research.

"Towards the 'perfect' weather warning" (Golding 2022) was produced by teams of authors dedicated to writing chapters that were then harmonized by the editor.

The citizen science (WMO 2021, 2024a) project was based in Massey University in New Zealand but drew on several grassroots projects around the world and collaborated with the Young Earth System Scientist (YESS) community (https://www.yess-community.org/) in two series of webinars.

The warning value chain (WMO 2024b) project was a collaboration with WGSERA based at the Bureau of Meteorology in Australia.

The impact-based warnings project (Potter et al. 2025) was a review, led from New Zealand and partnered with the impact-based forecast and warning services team of the WMO Public Weather Service Programme.

The project on forecaster decision-making was a HIWeather contribution to the Paris 2024 Research and Development Project (RDP) focused on a study of decision-making in high-stakes events (Masson et al. 2025, manuscript submitted to *Bull. Amer. Meteor. Soc.*). It was directed from NCAR and carried out with the Olympics forecasting team of Météo-France.

As a global project with participation from Europe, Australasia, China, and the United States, most of the team meetings were virtual. Physical workshops in 2016, 2017, and 2018 brought participants together for in-depth discussions and networking. Due to COVID, a planned workshop in 2020 was replaced by a virtual conference of five webinars followed by three 20-h workshops, each organized in three sessions, with participants joining for the session(s) that fitted their time zone. Subsequently, smaller meetings were held for individual cross-cutting projects until 2024 when a final workshop in Munich brought together learnings from the whole project.

From the outset, HIWeather sought to answer: "What makes an effective warning of high impact weather?" (Zhang et al. 2019). HIWeather adopted the convention that a warning is any communication of information that calls for action, including low-confidence communications that some countries, such as the United States, denote by other terms such as watch. Table 1 lists some key principles that were identified during the project. We concluded that an effective warning must enable its recipients to make appropriate decisions to protect themselves and their communities (Golding et al. 2019; Taylor et al. 2018), meeting three criteria:

- Mitigating actions (e.g., to protect property, delay travel, or prepare for possible loss of power supply) existed and were taken where appropriate, resulting in reduced negative impact.

Table 1. Key principles for the development of warning systems.

Warnings improve resilience by supporting better decisions.
Their value lies in the losses avoided.
Responses vary by hazard, culture, gender, and socioeconomic context
Communicating uncertainty effectively is essential for optimal decisions
Observations of hazards and impacts are vital for progress
Trust is foundational—built through open, quality communication
Involving operational staff in research enhances uptake and impact

- A timely warning was received, and the risks and suggested actions were understood well enough to lead to mitigating action (Scolobig et al. 2022; Potter et al. 2025).
- Information in the warning was sufficiently complete and accurate (including information about source, hazard, impact, location, time, and response).

3. Key outcomes

HIWeather brought together an unparalleled body of expertise from the physical and social sciences in the end-to-end weather warning chain. It demonstrated that effective warnings depend on understanding human behavior, communication, and decision-making as well as on the scientific accuracy of the forecast. Crucially, it showed that these domains must work in partnership—with each other and with decision-makers—to deliver warnings that lead to meaningful action.

These insights were embraced by the contributors to the project, by attendees at the meetings and conferences where the project was presented, by readers of our newsletters, guides, publications, and our book (Golding 2022), and enhanced the strategic and policy influence of HIWeather members. HIWeather significantly accelerated the transition toward an integrated, interdisciplinary approach to warnings by mobilizing a highly influential global community.

HIWeather's concepts have also been taken up by the anticipatory action community and are reflected in WMO's work on urban services, hydrology, and disaster risk reduction (e.g., REAP 2024) and in the next generation of WWRP research projects (Davis and de Coning 2024). Thanks to HIWeather's contributions, the scientific and operational communities are far better equipped to respond to the UN Secretary-General's call for "Early Warnings for All" by 2027 (WMO 2022).

a. Communication—A warning must promote response. Effective warning communication aims to raise risk awareness and enable people to take timely, suitable protective actions, consistent with the confidence and skill of the warner. Figure 2 illustrates the communication inhibitors that reduce warning effectiveness. HIWeather consolidated best practices and promoted new work in this area, producing a special issue of the *International Journal for Disaster Risk Reduction* featuring 14 articles[1] that represented the current state of knowledge in weather risk communication across five key themes as summarized by Taylor et al. (2018):

[1] https://www.sciencedirect.com/journal/international-journal-of-disaster-risk-reduction/vol/30/part/PA, last accessed 7 July 2025.

- Impact-based warnings can enhance understanding and support action, but evidence shows they do not always lead to protective behavior (see, e.g., Potter et al. 2018).
- Trust and uncertainty: Perceived inconsistency in weather and climate information may be more damaging to trust than uncertainty.
- Audience tailoring: Different audiences have different decision-making needs so require tailored communication.

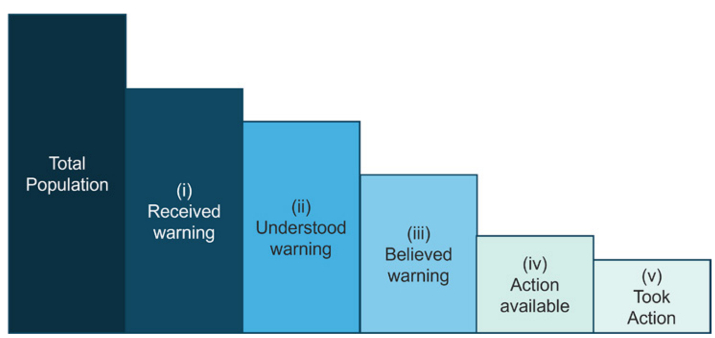

Fig. 2. Inhibitors of warning response: (i) recipients not receiving the warning, e.g., at night or during leisure activities; (ii) recipients not understanding the warning, e.g., if it is not in their first language or is too technical; (iii) recipients not believing the warning because they do not know or trust the source; (iv) recipients not perceiving that there is any protective action they can take; (v) recipients choosing not to take action, e.g., denying the threat to them or staying with a pet (after Perrels et al. 2013).

- Social media is increasingly important both for dissemination and as a source of real-time information.
- Contextual influences: Responses to warnings are shaped by social, cultural, political, and environmental factors, as well as access to information and personal characteristics.

An online workshop in 2022 addressed uncertainty, trust, and beliefs in high-impact weather communication. The synthesis of the discussions highlighted several principles for effective communication:

- Engage recipients as partners in a continuous, flexible interaction from design to implementation to postevent feedback (see, e.g., Scolobig et al. 2022).
- Acknowledge the inherent uncertainty of predictions and the operational constraints on forecasters (a survey of Météo-France forecasters involved in the Paris 2024 Olympics identified challenges of formulating advice in high-stakes forecasting environments; see Masson et al. 2025, manuscript submitted to *Bull. Amer. Meteor. Soc.*).
- Use a diverse range of media, e.g., by disseminating warnings through the Common Alerting Protocol (see https://wmo.int/site/wmo-common-alerting-protocol/about-cap).
- Communicate in recipients' first languages, using local idioms and respecting cultural contexts.
- Build trust and prepare audiences in advance.
- Include clear, specific information on hazard, impact, location, timing, and guidance on appropriate response, alongside the source of the warning and a link to further information. Potter (2021) identified guidelines for message length and format.
- Transparently communicate uncertainty—Clive et al. (2023) found that text is more effective than graphical representations such as shading. Communicating low-probability high-impact warnings is particularly challenging, but Taylor et al. (2024) found that people are sensitive to probabilities in this situation.
- Personalize messages with local impact details such as well-known locations or significant events.
- Evaluate communication strategies with trusted partners and the public prior to implementing them.

b. Forecasting impacts. Forecasting the impacts of weather-related hazards is central to the value of warning systems. It involves assessing effects on people, economic assets, and essential services—effects that ultimately influence human well-being through resilience (see Fig. 3). While individuals focus on impacts that affect them personally, governments, businesses, and humanitarian organizations are concerned with aggregated impacts on communities, regions, or countries.

Weather impacts span a vast array of disciplines, including economics, public health, engineering, and psychology. HIWeather contributed substantially to the growth of research in this area, promoting interdisciplinary collaboration across their differing languages, cultures, and approaches. National Meteorological and Hydrological Services (NMHSs) in developed countries are increasingly hiring social scientists to foster these partnerships.

HIWeather advanced risk and impact modeling through studies such as those by Terti et al. (2019) and Hemingway and Robbins (2020) and developed methods to estimate changes in risk linked to weather warnings (e.g., Lazo et al. 2020; Mills et al. 2019). It also advanced understanding of methods for collecting, postprocessing, and using socioeconomic data to quantify impacts and assess exposure and vulnerability (e.g., Harrison et al.

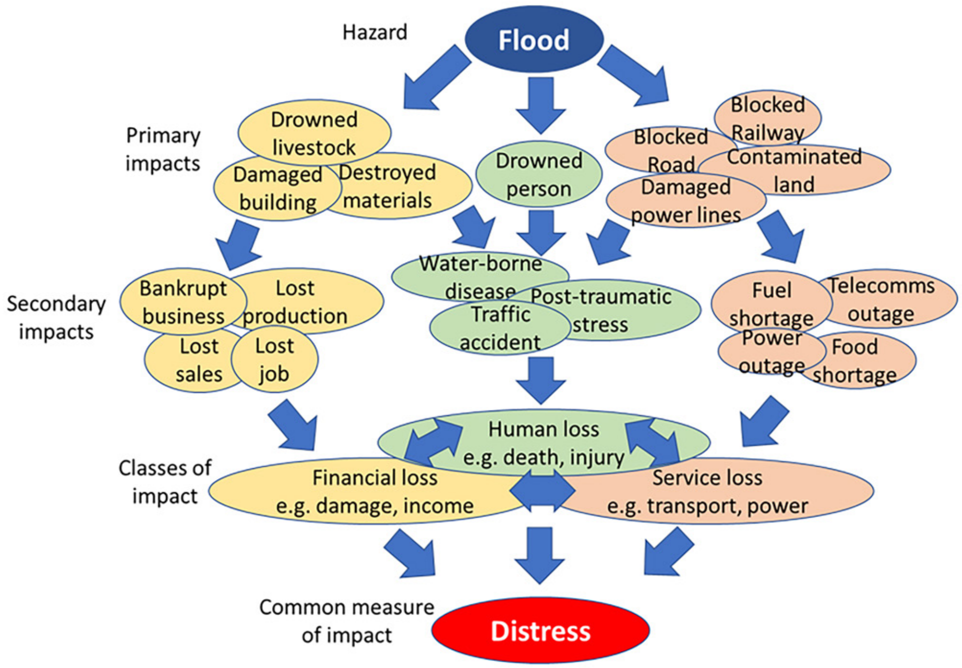

Fig. 3. Illustration of the complexity of even a simplified hazard–impact cascade for just one hazard (riverine flooding) based on a 3-fold classification into financial (orange), human (green), and service (pink) impacts. While impacts are often aggregated by monetizing them, this version offers distress as the common measure (from Golding 2022).

2021, 2022; Mills 2020; Wyatt et al. 2023), including through innovative data sources like social media and crowdsourcing, while noting that these come with limitations of reliability (Spruce et al. 2021; Wyatt et al. 2023). These efforts highlighted the need for NMHSs to invest in robust workflows and storage platforms that give consistent, accessible impact data for significant hazards (Wyatt et al. 2024) for application to verification/evaluation, situational awareness, model development, and long-term monitoring.

Citizen science was identified as a key contributor to user engagement and sourcing of data. A research project generated good practice guides for the use of citizen science (WMO 2021) and crowdsourcing (WMO 2024a), the latter incorporating 10 illustrative case studies, including "My aching joints tell me it will rain" and "Let's Talk Weather in Ghana." The research highlighted how engaged citizens can improve risk understanding and communication, fill observational gaps, and enhance decision-making (Tan et al. 2022; Vinnell et al. 2021), while user feedback can also enhance situational awareness and support continuous improvement. Crucially, effective warnings depend on warning providers and users understanding each other's needs and constraints.

Impact-based forecasting and warning (IbFW) enhances traditional fixed-threshold hazard warnings by using the forecast impact of the hazard both in the decision to issue warnings and in their content. For example, a strong wind warning may be issued when a certain wind speed threshold is forecast (a hazard-based warning), or it may be issued when a certain level of damage is forecast (an impact-based warning).

HIWeather promoted studies of the effectiveness of impact-based warnings. It found that while impact-based warnings and behavioral recommendations both improved intended responses, only the latter influenced actual behavior (Weyrich et al. 2018). It also found that inconsistent warnings significantly reduce intended responses, while crowd-sourced information enhanced decision-making and confidence (Weyrich et al. 2019, 2021).

HIWeather, together with the U.K.-funded Science for Humanitarian Emergencies and Resilience Program (see https://www.shear.org.uk/home.html), identified that despite a high-level shared understanding of IbFW, different methodologies are being implemented (Robbins et al. 2022). HIWeather established a research project to identify challenges and solutions in IbFW and define future research directions (Potter et al. 2025). A literature review was followed by an online workshop series that attracted over 350 participants from a wide range of backgrounds, focusing on three themes: underpinning data and model integration, people-centered warnings, and multihazard approaches. Participants shared mixed views on the effectiveness of impact-based versus hazard-based warnings, emphasized the importance of partnerships for accessing socioeconomic data, and recommended a cautious, stepwise implementation strategy. A follow-up workshop in 2023 identified three key priorities:

- Obtaining impact data (including avoided losses and behavioral responses) for verification, addressing issues of governance and restrictions on sharing (see, e.g., Kox et al. 2018; Kox and Lüder 2021; Harrison et al. 2022).
- Assessing the value of dynamic exposure and vulnerability data, tailored warnings, and quantitative modeling relative to qualitative approaches.
- Communicating uncertainty effectively.

c. Understanding and forecasting weather-related hazards. Forecasting weather-related hazards is fundamental to effective warning services and relies on accurate observations and realistic models from a range of diverse disciplines, including meteorology, hydrology, geology, and atmospheric chemistry, each with its own terminology and research culture. Building partnerships with them requires time and effort to overcome institutional barriers and align objectives. Majumdar et al. (2021) conducted a comprehensive review of the current state of hazard monitoring and forecasting, the key recommendations of which are shown in Table 2. It is evident that machine learning offers opportunities to address several of these challenges.

HIWeather partnered with W2W (Craig et al. 2021) to investigate predictability of high-impact weather through theory, field experiments, and modeling. W2W focused on upscale error growth, cloud-scale uncertainty, and local weather predictability. This partnership promoted collaborative science through a series of co-organized international workshops: the 2017 Conference on Predictability and Multi-Scale Prediction of High Impact Weather, the 2019 Cyclone Workshop, and the 2022 Mathematics of the Weather workshop.

Team members contributed to and (co)led activities in many related international field programs, including those listed in Table 3. Most of these were focused on very short range forecasting and nowcasting of small-scale weather phenomena that are highly variable and strongly influenced by local factors. Progress in forecasting at these scales has been slower than hoped for at the beginning of HIWeather.

Table 2. Recommendations for improving hazard prediction.

Enhance urban monitoring, ubiquitous sensing, and social media analysis to improve situational awareness
Identify and detect precursors of severe weather
Develop physically consistent, multiscale initial states and ensemble perturbations for kilometer-scale models
Couple hazard and weather prediction models, harmonizing shared variables, data standards, and uncertainty representation
Improve communication and use of probabilities in warnings and decision support
Research the specific forecast information needs of emergency responders
Deploy new instruments, radar technologies, satellites, and citizen science to provide observational input to high-resolution models
Focus on prediction of extremes

Table 3. Field experiments that HIWeather team members were active in.

Short name	Year(s)	Full name	Reference
HyMEX	2010–20	Hydrological Cycle in the Mediterranean Experiment	Ducrocq et al. (2019)
SCMREX	2013–18	Southern China Monsoon Rainfall Experiment	Luo et al. (2017)
SURF	2015–16	Study of Urban Impacts on Rainfall and Fog/Haze	Liang et al. (2018)
NAWDEX	2016	The North Atlantic Waveguide and Downstream Impact Experiment	Schäfler et al. (2018)
ICE-POP 2018	2018	International Collaborative Experiments for PyeongChang 2018 Olympic and Paralympic winter games	https://amt.copernicus.org/articles/special_issue10_1112.html
RELAMPAGO	2018–19	Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations	Nesbitt et al. (2021)
MedCyclones	2020–	COST Action on Mediterranean cyclones	Khodayar et al. (2025), Flaounas et al. (2022)
FESSTVaL	2021	Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg	FESSTVAL Team (2023)
SMART 2022	2022	Sciences of Meteorology and Artificial intelligence in Research and Technology for the Beijing 2022 Winter Olympics	
PARIS 2024	2024	WWRP Paris Olympic Games Research and Development Project	Masson et al. (2025, manuscript submitted to *Bull. Amer. Meteor. Soc.*)
NAWDIC	2025–26	North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign	https://www.nawdic.kit.edu/

d. Evaluating the warning value chain. HIWeather built a cross-disciplinary team to evaluate the effectiveness of the warning value chain, drawing on expertise from social, economic, environmental, and behavioral sciences to build knowledge of how information flows from forecast to action. Understanding of warning performance requires a portfolio of measures of the components of the warning chain together with an assessment of the outcome in terms of avoided losses. Aspects of forecast accuracy were addressed in the Mesoscale Verification in Complex Terrain project (Dorninger et al. 2018) and in two International Verification Challenges focused on user-oriented metrics and on use of nontraditional data. An investigation of the use of tropical cyclone ensemble products by operational forecasters (Titley et al. 2019) revealed concerns about data quality, unfamiliarity, and communication of uncertainty.

HIWeather collaborated with WGSERA to review and promote previous use of value chain concepts in weather and climate services, e.g., by Perrels et al. (2013). The “five valleys of death” conceptual model (Fig. 4) was conceived to highlight critical points where information may be lost. This informed the development of a comprehensive postevent questionnaire to assess performance of the warning value chain during high-impact events. A toolset, including the questionnaire template (Fig. 5), guide, video, and rapid assessment tool, is freely available online (https://doi.org/10.5281/zenodo.13966993) (Ebert et al. 2024) and is being used in both operational and educational settings. Using assessments of several events in 2021, Golding et al. (2023) identified common communication weaknesses as well as some forecast failures. A survey of project members in 2022 identified several NMHSs, including those of Norway and Argentina, that had been influenced by the concept, and it is reflected in the bridges between components of the value cycle in the EW4All plan.

4. Summary

HIWeather built a vibrant, cross-disciplinary community of researchers and practitioners committed to improving weather-related warnings. This community advocated investment in cross-disciplinary research for sustainable multihazard IbFW and promoted the importance

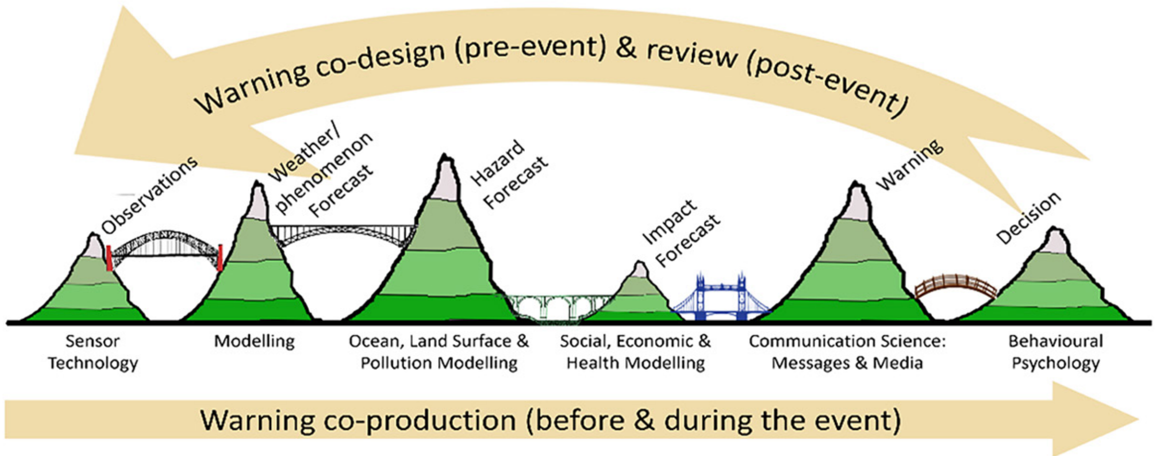

Fig. 4. The HIWeather concept of the warning value chain (after Golding et al. 2019).

of collaboration across scientific, operational, and societal domains. Many members are now applying their expertise to other national and international initiatives including EW4All and the Forecasting a Continuum of Environmental Threats (FACETS) program in the United States (Rothfusz et al. 2018).

A key legacy of HIWeather is its influential publication, Toward the Perfect Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication (Golding 2022), which has had 117 000 chapter downloads and 51 citations to date. Along with other HIWeather outputs, this serves as a foundational resource for those designing, implementing, or teaching about warning services.

Central to HIWeather's success has been the concept of "Warning Chain Thinking," through which the warning system is viewed holistically. This perspective highlights the critical role of partnerships—between disciplines, institutions, decision-makers, and end users—in ensuring that warnings are not only timely and accurate but also actionable and trusted. This philosophy strongly influenced the goals of EW4All.

HIWeather forged strong links with the humanitarian community through the Integrated Research in Disaster Risk (IRDR) project (https://www.irdrinternational.org/) and the anticipatory action initiatives of the International Federation of Red Cross Red Crescent Societies (IFRC).

A short list of key publications is provided in the appendix.

5. Looking forward

The HIWeather project was very successful in advancing several aspects of warnings and, in particular, the end-to-end view of the effective warning system. However, there were several project objectives in forecasting and warning that were not achieved, and we particularly note the following outstanding challenges.

While convection-permitting models have enabled great progress in the prediction of mesoscale weather systems, less progress was made than hoped in the prediction of convective hazards due to inadequate resolution of convective structure,

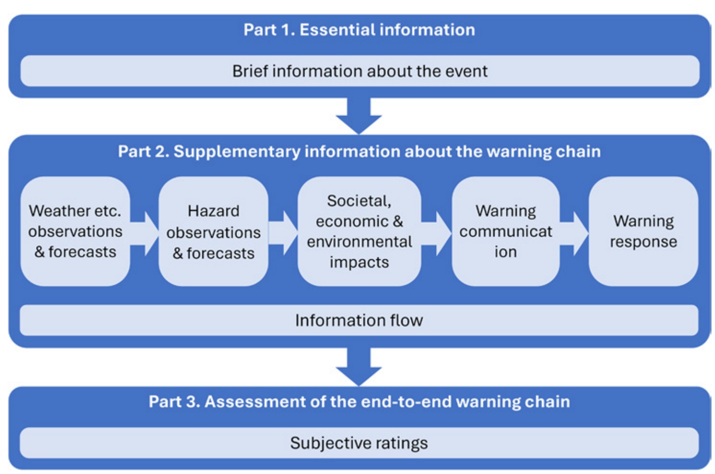

Fig. 5. Outline of the value chain postevent review template (from Hoffmann et al. 2023).

lack of observations, limitations of data assimilation schemes designed for larger scales, and inadequate representation of the interactions among turbulence, microphysics, and radiation in convective clouds. While progress has been made in the Warn-on-Forecast System for mesoscale convection in the United States (e.g., Heinselman et al. 2024), research shows that subkilometer gridlength models will be required in other climate regimes. Such models are only currently affordable in very restricted domains. Alternative approaches using machine learning may be more successful (see, e.g., Flora and Potvin 2025).

Forecasting compound hazards and understanding complex cascading risks has advanced, but effectively communicating the resulting risks remains a major challenge. When hazards stem from technological failures triggered by natural events—such as dam overtopping during extreme floods—questions of responsibility and governance complicate warning delivery.

Warnings are most effective when they suggest specific actions. However, ideal responses vary by individual. Technology is available to tailor warnings to individual needs, and artificial intelligence (AI) will soon enable personal risk tolerances to be learned and applied. However, these approaches may provide inconsistent advice and exclude the most vulnerable populations.

The value of a warning system lies in the impacts that did not occur but would have occurred without the warning. Estimating these counterfactuals is challenging and will require innovative modeling methods. For example, in England, a model is used to assess the flood damage that would have occurred without flood defenses.

HIWeather emphasized the importance of viewing the warning system as a complete chain. Applying formal systems analysis would deepen understanding of dependencies and sensitivities across the chain, improving the design and evaluation of warning services.

As the weather and climate enterprise evolves, it will require new voices from diverse disciplines. HIWeather's legacy encourages openness to these perspectives, fostering innovation and inclusivity in future warning systems.

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Data availability statement. The results presented in this article are based on data that are openly available at locations cited in the references.

APPENDIX

Key Publications

The following key publications were produced. See WMO (2025) for a comprehensive list.

Special issue on Communication (*International Journal of Disaster Risk Reduction* 2018).

Special issue on Citizen Science (*Australasian Journal of Disaster and Trauma Studies* 2021).

"High Impact Weather (HIWeather) Citizen Science Guidance: For weather, climate and water projects" (WMO 2021).

"Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges" (Majumdar et al. 2021).

"Towards the 'Perfect' Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication" (Golding 2022).

"HIWeather Crowdsourcing Guidance Note: Harnessing the Power of the Crowd" (WMO 2024a).

"Value chain approaches to describe, improve, value and co-design early warning systems" (WMO 2024b).

"Research gaps and challenges for impact-based forecasts and warnings: Results of international workshops for High Impact Weather in 2022" (Potter et al. 2025).

Special collection on applications of the warning value chain (*Weather, Climate, and Society* 2025).

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