WWRP 2025 - 1

WWRP High Impact Weather (HIWeather) Final Report

January 2015–December 2024

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER RESEARCH PROGRAMME

HIWeather

Forewords

The increasing frequency and intensity of hazardous weather events, such as extreme rainfall, pose significant challenges to communities, economies, and ecosystems around the world. To save lives and livelihoods, it is no longer enough to know what the weather will be. We need to know what it will DO through impact-based forecasting.

The WMO High Impact Weather (HIWeather) Project of the World Weather Research Programme has provided a critical framework for advancing our understanding and communication of severe weather. It has helped broaden the focus away from just forecast accuracy to a much broader inter-disciplinary approach, embracing science and social science, and risk management and response.

We need to be mindful of the fact that even a perfect weather warning will fail if it does not reach the people who need it and lead to action on the ground.

One of the main priorities of WMO is to expand Multi-Hazard Early Warning systems to ensure global protection. HIWeather is one of the important foundations of the Early Warnings for All initiative.

This report represents the culmination of dedicated efforts by the international research and operational meteorology communities. Through collaboration and innovation, the project has delivered valuable insights, tools, and partnerships that lay the foundation for better resilience.

I commend the contributions of all partners and experts involved in this work, whose efforts have strengthened the global capacity to anticipate and respond to high-impact weather and to build more resilient and sustainable communities and economies.

2025 marks the 75th anniversary of WMO as a UN specialized agency under the slogan of Science for Action. HIWeather will leave a lasting legacy of how we improve and transform the science of weather prediction into a vital service for society.

Celeste Saulo
WMO Secretary-General

The High Impact Weather (HIWeather) Project, a core project of WMO's World Weather Research Programme (WWRP), represents a landmark in advancing global capabilities for understanding, predicting, and responding to high-impact weather events. Over the past decade, HIWeather has brought together scientists, operational meteorologists, social scientists, emergency managers, and policymakers to advance the science and practice of accurate, timely, and actionable weather prediction for society.

HIWeather has championed the integration of physical and social sciences to understand how users of forecast information make decisions, and where, in the complex and iterative relationship between users of forecast information, researchers and operational practitioners, gaps can be closed to produce more desirable outcomes. The project has emphasized the critical importance of communication, helping to shape how warnings are delivered and understood across different communities and cultures. From advancing impact-based forecasting to pioneering collaborative testbeds and real-world demonstration projects, HIWeather has laid the groundwork for more people-centered and impact-aware weather services.

The HIWeather project has produced a substantial legacy, in terms of the professional relationships it created, the outputs that will guide the weather forecasting and preparedness community for years to come, and the spark for new projects that carry forward the achievements of HIWeather. The WWRP has launched three new projects: Integrated Prediction of Precipitation and Hydrology for Early Actions (InPRHA), Progressing EW4All Oriented to Partnerships and Local Engagement (PEOPLE), and Urban Predictions, Risk assessments, Early warnings, Data integration, Inclusive governance, Community awareness, and Transformative actions (Urban-PREDICT) in 2024 and 2025. Each of these new projects builds on the outcomes of HIWeather by adopting an analogous interdisciplinary approach to advance use-inspired research, its operational adoption, and use by a wide range of constituencies. Furthermore, each of the five new WWRP core projects is co-chaired by a social scientist, to ensure that the project design incorporates diverse research perspectives, and that the project outcomes have greater societal benefit.

Importantly, HIWeather has not only deepened our scientific understanding of hazardous weather phenomena, but also empowered communities through enhanced risk awareness and decision-making capacity. The project has set a high standard for future research, ensuring that the next generation of weather services will be more integrated, inclusive, and resilient. I am indebted to Drs. Brian Golding, David Johnston, who left us far too soon, and Sally Potter for their leadership of HIWeather, and to all the researchers and practitioners who contributed to this project.

Chris Davis
Chair of WWRP

DEDICATION TO THE MEMORY OF DAVID JOHNSTON

This publication is dedicated to Distinguished Professor David M. Johnston, who co-led the HIWeather project between 2015 and 2021, and sadly and suddenly passed away in February 2025. David was the Director of the Joint Centre for Disaster Research at Massey University in New Zealand. His influence throughout the project and in the careers of many of the researchers involved is leading to closer integration of physical and social sciences. His invaluable contributions have significantly advanced our understanding and resilience to natural hazards, and his legacy will continue to inspire and guide future research in this critical field.

EXECUTIVE SUMMARY

During the ten years of its work, the HIWeather project of the World Weather Research Programme has been influential in changing the focus of weather forecasting and warning services from a narrow concern for the accuracy of the forecast information to a much broader inter-disciplinary view of the end-to-end forecasting and warning chain and its effectiveness in reducing negative impacts. It has built momentum in the partnership between the social and physical sciences in meteorology and has grown a community of researchers and practitioners who both understand the importance of working across disciplines and are passionate about the value of warnings in reducing the impact of weather-related hazards. This community and the evidence assembled by the project have provided a foundation for the UN Early Warnings for All initiative as well as for the next generation of research projects, both within and outside the WWRP.

HIWeather promoted "Warning Chain Thinking", focusing attention on the warning system as a whole, and emphasising the role of partnerships between disciplines, organisations, decision makers and users. This was reflected in its book: "Towards the Perfect Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication" that provides a key resource for those designing and building warning services. Project outputs, including the book, several WMO guides, and a host of journal publications, are increasingly being used in a variety of education, training and operational settings.

INTRODUCTION

The WMO World Weather Research Programme (WWRP), High Impact Weather project (HIWeather), is one of three projects initiated following the completion of the Observing System Research and Predictability Experiment (THORPEX) project in 2014, the other two being the Polar Prediction Project (PPP) and the Sub-Seasonal to Seasonal Prediction (S2S) Project. HIWeather started in 2015, the same year that governments agreed to the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals, and the Paris Agreement on Climate Change. A key component of the plan for HIWeather was the NAWDEX experiment to extend the achievements of THORPEX in improving understanding of processes that generate severe weather and the downstream consequences. However, development of the implementation plan emphasised the need to have a much greater engagement of social science than had been achieved in THORPEX and this came to be the central theme of the project. In light of this, key foci of the project became the end-to-end warning value chain, from observation and forecast to warning, communication and response; engaging citizens in the warning process, both as providers of local data and knowledge, and as experts in the needs of the community; and probing the challenges and benefits of impact-based forecasting and warning. The relationship between stakeholders at the response end of the warning chain is an established role of the Disaster Risk Management community, so engagement with this community was a natural and necessary development within HIWeather, leading to HIWeather becoming a key contributor to the evolution of Early Action, Anticipatory Action and Forecast-Based Financing. Resulting from its linkages across the communities of physical and social scientists, HIWeather also provided the underpinning knowledge and understanding needed for development of the strategy for delivering Early Warnings for All (EW4All), following the call by the United Nations Secretary-General in March 2022 for everyone on Earth to be protected by an early warning system within five years.

THE WWRP CONTEXT

Although it formally started in 2015, for most of its duration HIWeather, along with the Polar Prediction Project (PPP) and Sub-Seasonal-to-Seasonal (S2S) Project, was managed as part of the WWRP Implementation Plan (IP) for 2016–2023. The deliverables of this plan were aligned with the over-arching WMO Strategic Plan 2016–2019, which was approved by the World Meteorological Congress at its seventeenth session in May–June 2015 setting priorities for the activities of WMO and its Members to sustain and advance the hydrometeorological infrastructure and to improve our knowledge of the Earth system through science and technology.

The WWRP IP focused on four societal challenges: High Impact Weather, Water, Urban and New Technologies. The High Impact Weather challenge identified that high-impact weather events have a growing societal and financial impact in a changing climate, on a growing population and on the infrastructure that society depends upon. Significant progress and advances in scientific understanding, monitoring, prediction, computing, telecommunications, and specialized services have been achieved in recent years, but major disasters constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems faced by society. Identifying and effectively addressing these gaps requires the weather communities from governmental services, academia and the private sector, together with social and other interdisciplinary scientists, to work in close collaboration with those affected by weather-related hazards and those charged with the responsibility of managing risks. Seamless prediction of high-impact weather events at all time scales (from nowcasting to seasonal prediction) has to be improved, with a particular focus on local scales where decisions need to be made. Appropriate and targeted communication of forecasts and warnings, together with user-oriented verification is crucial for capitalizing the achievements being made in prediction of high-impact weather events. Within the High Impact Weather challenge, the aim of the HIWeather project was to contribute to all five of the WWRP IP Action Areas: Address Limitations; Uncertainty; Fully Coupled; Applications and Verification. Its vision was to "Promote cooperative international research to achieve a dramatic increase in resilience to high-impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications".

It set out to address the forecasting and warning of five main hazard groups:

Floods
including coastal, riverine and surface water floods together with the associated landslides hazard.

Wildfires
usually associated with heat and drought.

Extreme Wind
associated with both mid-latitude and tropical cyclones and with severe convection (including tornadoes).

Disruptive Winter Weather
covering hazards from solid and mixed precipitation, ice and fog.

Heatwaves and air pollution
taken together as their impacts on health are assessed through epidemiology.

STRUCTURE AND OVERVIEW

The project was structured in five disciplinary pillars with cross-cutting projects to bring them together. In the first few years, work focused on the pillars, assessing and promoting research into the scientific components of forecasts and warnings:

01
Predictability and Processes

Improve knowledge and understanding of the processes that generate weather-related hazards so as to assess their predictability – with a strong contribution from the associated Waves-to-Weather project linked to HIWeather through the Processes and Predictability task team.

02
Multi-scale Hazard Forecasting

Develop multi-scale coupled forecasting systems of weather-related hazards, including new observation sources, advances in data assimilation and modelling and ensemble prediction, and definition of new products – primarily carried out through involvement of HIWeather members in linked field experiments and their associated analysis, including SURF, HyMEX, SCMREX, RELAMPAGO, HIGHWAY, NAWDEX, FESSTVaL, ICE-POP2018, SMART2022, Paris 2024. Directions for research were identified in a review of short-range forecasting capability that was published in the Bulletin of the American Meteorological Society (BAMS).

03
Impacts, Vulnerability and Risk

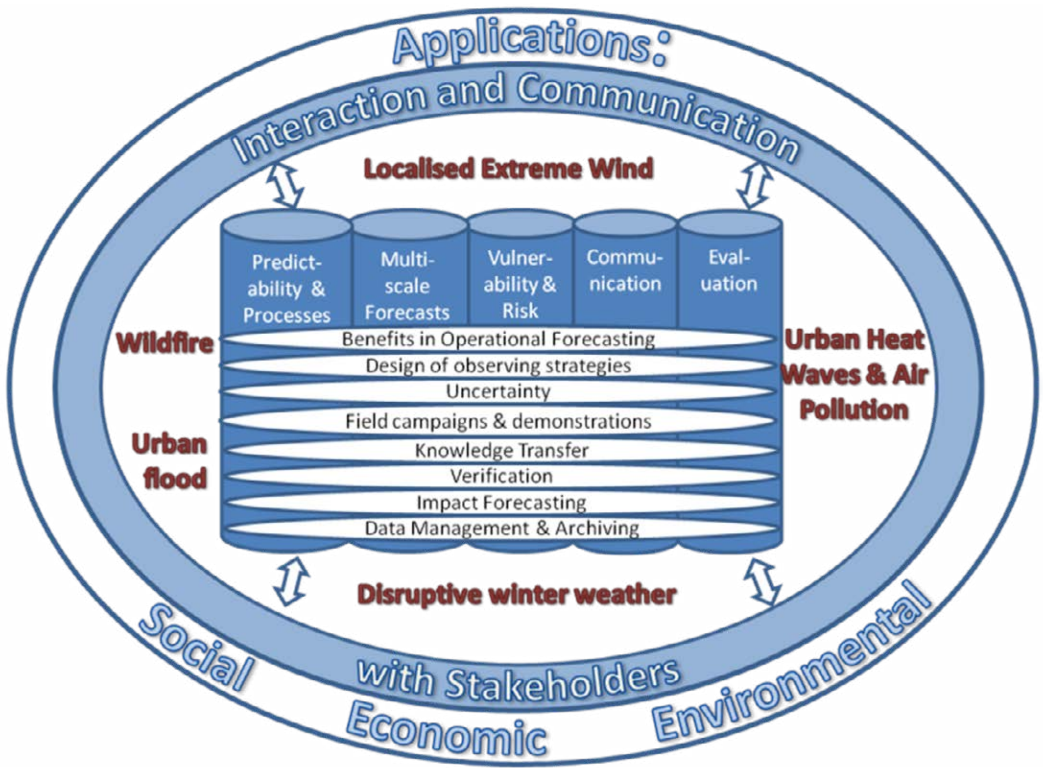
Improve knowledge, understanding and modelling of the exposure and vulnerability of society, businesses, environment and infrastructure to weather-related hazards and obtain data and develop tools and models to assess the resulting risk. HIWeather members contributed to building up the research community in this area through promotion and publication. Additionally, the Flagship projects on Citizen Science, Value Chain and Impact-based Forecasting and Warning have all placed this area at the heart of their work. The relevant section of the HIWeather book covers this in detail. Its material has been incorporated into the WMO Guide on Urban Services and is being incorporated into the Guide to Hydrological Impact-based Forecasting.

04
Communication

Improve knowledge and understanding of the processes and variables that influence different stakeholders' decisions using high-impact weather forecasts and warnings, and of the characteristics of information communication that lead to effective responses. HIWeather members contributed substantially to growing the research community through promotion and publication, including an influential special issue in the International Journal of Disaster Risk Reduction. This area has also been taken forward in all of the flagship projects and is treated at length in the HIWeather book. This work has also been very influential in other aspects of WWRP research and more broadly in WMO.

05
Evaluation

Develop improved methods of verifying forecasts, hazard warnings and people's responses so as to permit evaluation of each stage in the complete production chain. The Evaluation task team extended the scope of existing work in verification through the MesoVICT project and the two verification challenges focused on user-oriented verification and use of non-traditional observations in verification. The team then took on the challenge of evaluating end-to-end performance within the Value Chain flagship project.



As the mid-point of the project approached, a selection of cross-cutting projects emerged to take the work forward. These were designated flagship projects and focused on:

- A book, "Towards the perfect weather warning" that pulls together the knowledge accumulated in the first part of the project in a form suitable for use by professionals in weather services and emergency management agencies.
- The use of citizen science both to engage stakeholders in the warning process and as a source of information about hazards and their impact.
- Analysis and evaluation of the forecasting and warning value chain as a connected system consisting of multiple sources of expertise, linked by communication channels and delivering information that enables the recipient to take protective decisions.
- Analysis of gaps in our understanding in developing impact-based forecasting and warning systems, including data and partnership needs, communication and decision-making.
- Analysis of the forecasting and decision-support processes for high-stakes events to assess what factors influence them (e.g. time pressures, stress management, asymmetric penalties, recent successes/problems) and the role of predictability limitations and corresponding uncertainty.

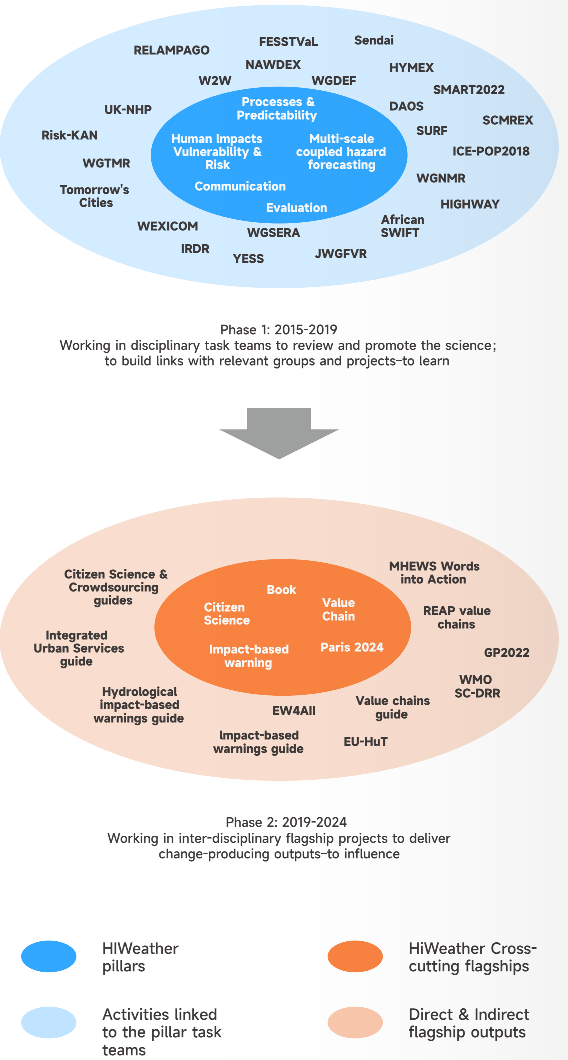
In pursuing these goals, the following overarching principles were followed:

- Forecasts and warnings increase resilience when they improve the decisions made by users.
- The responses of service providers and users to forecasts and warnings vary with hazard, country, culture, gender, experience, socio-economic status and other factors.
- Optimal decisions require communication and interpretation of uncertain forecasts.
- Advances in forecasting, warning and communication of hazards require collection and analysis of observations of their occurrence and their impacts.
- An effective forecasting and warning service depends on trust. An important component of building trust is evaluation and open communication of relevant quality information from every link in the chain.
- Engaging operational services and staff in the design, execution, and/or interpretation of the results of experiments often instils greater appreciation, implementation, and realizations of benefits.

PARTNERSHIPS

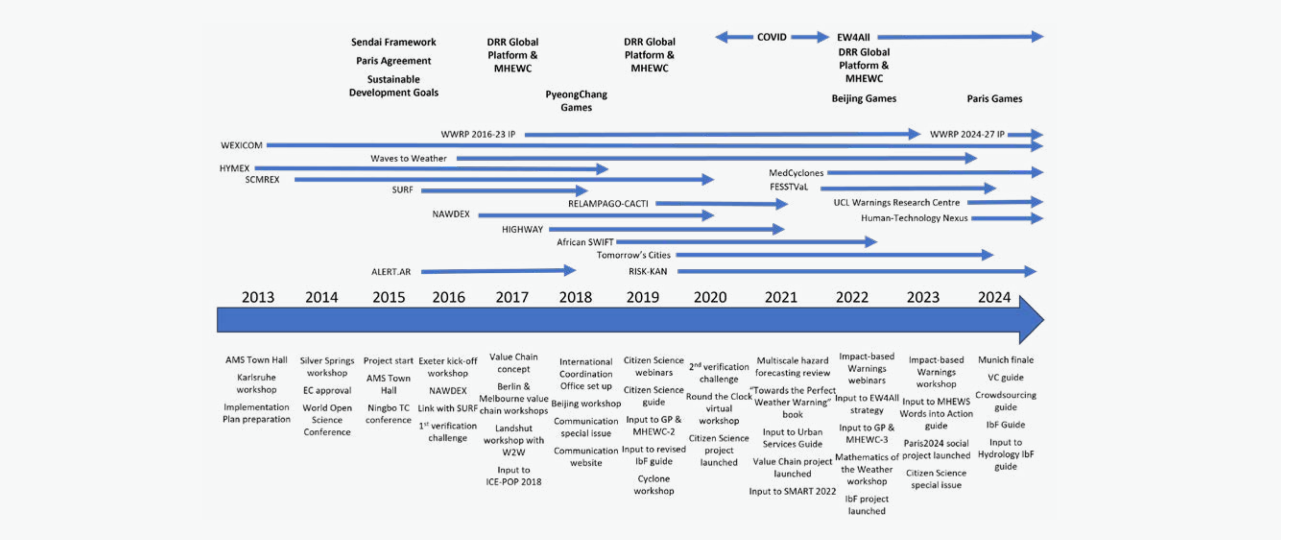
From its conception, HIWeather was a project that would rely on partnerships in its key areas of research. Each part of the project developed different ways of achieving this. In the processes and predictability component, the simultaneous initiation of a major funded research project, Waves-to-Weather, in Germany which was also a leading organiser of the NAWDEX field experiment and a partner in subsequent field experiments, resulted in most of the activity being carried out by this partner. In the Multi-Scale Hazard Forecasting component, the strength of research in the major modelling centres led the team to partner with a variety of teams carrying out modelling work and field experiments to improve prediction. In the Communication component, existing research was much sparser, but the WWRP Working Group on Societal and Economic Research Applications (WGSERA) had drawn together some of the foremost researchers. HIWeather therefore partnered with WGSERA, providing a focus for growing the research body in this area. Similarly, for the Evaluation component, initial work with the Joint Working Group on Forecast Verification Research formed the baseline for expanding into considerations of evaluating the full forecasting and warning value chain. This component also developed an interest in Citizen Science leading to partnership with several Citizen Science projects and with the Young Earth System Scientists (YESS).

The remaining component, Impacts, Vulnerability and Risk had no natural partner to work with. Or rather, its numerous potential partners were spread across engineering, epidemiology, economics and a host of other disciplines from which it drew its members. Two key partner projects were successfully initiated: Tomorrow's Cities in the UK GCRF programme has focused on avoiding the creation of risk using a sophisticated impact scenario modelling approach, while the Human-Technology nexus (HuT) has corralled risk-reduction



activities in several countries to cross-fertilise approaches to impact modelling and risk reduction. Issues of compound hazards were addressed through links with the Co-Operation in Science and Technology - Disaster risk Advanced Modeling and Observing Capabilities for multi-scaLe Evaluation of hazardS (COST DAMOCLES) project and establishing a partnership with the Risk-Knowledge Action Network (Risk-KAN) which led to WWRP joining with Future Earth, IRDR and WCRP as a sponsor. Avoiding both a narrow focus on one area and a superficial approach to all of them has been a challenge, which was met by focusing on the key issues in providing the impact information required for Impact-based Forecasts and Warnings (IbFWs). Hence it developed partnerships with the WMO working groups developing guides for IbFW as well as weather services that are actively developing such systems. The unifying theme that has integrated these multiple approaches to partnership is the achievement of a seamless value chain that optimises the usefulness, usability and use of weather-related warnings, as exemplified in the HIWeather book, Towards the Perfect Weather Warning. In this regard, HIWeather has partnered with scientists in organisations as diverse as the International Red Cross, Practical Action, the United Nations Office for Disaster Risk Reduction, Future Earth, Integrated Research in Disaster Reduction, the UK Disasters Research Group, and many parts of the WMO Services Commission as well as several NMHSs.

TIMELINE



KEY OUTCOMES

The HIWeather project brought together an unparalleled body of expertise from the physical and social sciences in the end-to-end warning chain. The underlying messages are that effective warnings depend on the application of expertise from both physical and social sciences and that these experts must work in partnership with each other and with decision makers. These have been taken up by the several hundred contributors to the project, by attendees at the many high-profile meetings and conferences where the project has been presented, by readers of our newsletters, guides, publications and our book, and by the strategic and policy influence of HIWeather members. While a move towards this end-to-end, interdisciplinary view of the warning process may have happened without HIWeather, the project has certainly helped and accelerated that evolution through promotion from such an influential community. As a result, an increasing number of national weather services is adopting a value chain or value cycle approach to designing its warnings systems. HIWeather warning system concepts have been adopted in the Anticipatory Action community and are reflected in WMO activities in urban, hydrological and disaster risk reduction services, as well as in the design of the next generation WWRP research projects. As a result, the scientific community is much better positioned to respond to the United Nations Secretary-General's call for everyone to be protected by an early warning system (EW4All) than might have been the case without HIWeather.

RESEARCH ACHIEVEMENTS

Predictability and Processes

(Leads: George Craig, Michael Riemer)

The goal of the Predictability and Processes (P&P) theme was to accelerate the increase of knowledge and understanding of processes that lead to hazardous weather and hence their potential predictability. The task team was challenged to explore the aspects of the large-scale slowly-evolving circulation that create the conditions for high-impact weather, the faster, small-scale roles of moist diabatic processes and surface processes in realizing it, and the mechanisms that produce the quasi-stationary behaviour often associated with the most severe events. In light of its work, the team was asked to identify whether the atmosphere is fundamentally less predictable than usual during high-impact weather events.

The implementation plan envisioned that science questions independent of the differences between hazards and between regions may integrate research efforts and lead to cross fertilization. It turned out that this strategy was too ambitious without the impetus of funding. Instead, task team members linked with and co-organized other relevant projects. Official endorsement by HIWeather helped them acquire funding from national funding agencies. By this means, the theme helped to promote a collaborative, international community and thereby fostered the desired scientific advances Reviewing progress and building community was accelerated with the co-organized ***Conference on Predictability and Multi-Scale Prediction of High Impact Weather*** (Landshut, Germany, 2017) and continued with the ***Cyclone Workshop*** (Seeon, Germany, 2019) and sessions at international conferences (e.g. EMS and IUGG ***Atmospheric Dynamics*** session). Of particular importance for bringing rather separate communities closer together was the workshop ***Mathematics of the Weather*** (Bad Orb, 2022).

Field campaigns

Important topics were advanced in the context of field campaigns, co-led and co-designed by P&P team members. The ***North Atlantic Waveguide and Downstream Impact Experiment*** (NAWDEX, 2016, ***http://nawdex.ethz.ch/***) explored the impact of diabatic processes on disturbances of the jet stream and their influence on downstream high-impact weather through the deployment of synergistic airborne and ground-based observations from the entrance to the exit region of the storm track (Schäfler et al. 2018). About fifty scientific articles have been published (***http://nawdex.ethz.ch/publications.html***) that advance our understanding of the role of moist diabatic processes.

The North Atlantic Waveguide and Downstream Impact Experiment, See Schaefler et al, 2018, Bull Amer Meteorol S. DOI: https://doi.org/10.1175/BAMS-D-17-0003.1

A further problem highlighted in the implementation plan was the role of near-surface and boundary-layer processes in weather-related hazards, e.g. in the initiation of convection. In this context, the ***Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg*** (FESSTVaL in 2021 – ***https://fesstval.de/en***) used a unique set-up combining a dense spatial measurement network with high-quality routine remote sensing observations, further complemented with microwave profilers, x-band radar and Doppler Lidars. These hierarchical measurements allowed the investigation of boundary layer structures, cold pools, and wind gusts. The campaign was accompanied by a lecture series (***https://fesstval.de/en/summer-school/translate-to-english-lecture-series-2021***) to educate the next generation of scientists in this important area. The analysis of the data is ongoing, and already more than ***ten publications*** document the scientific achievements, including a final report.

In the context of severe convection, data from the ***RELAMPAGO field campaign*** were used to: (i) describe the types of convection and their environments responsible for hail in central Argentina, and (ii) analyse the spatial and temporal accuracy of passively crowd-sourced hail reports from Twitter. Results were used to evaluate SMN watch and warning accuracy and to identify the types of hail environments that SMN excel at predicting and those that they have more challenges with (Elkins, 2022).

Two task team members are (co-)leading the planning of the ***North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign*** for early 2026. NAWDIC is an international field campaign focusing on mid-latitude atmospheric dynamics with the aim of providing detailed observations for improving the understanding and modelling of the mesoscale tropopause structure, the ***dry intrusion air stream*** - PBL interaction, and their relation to high-impact weather in the North Atlantic region in winter. NAWDIC will build on the successful NAWDEX campaign and on related ***Waves to Weather*** research, continuing to address the key challenges identified for the theme.

Links to large-scale research projects

The COST Action on Mediterranean cyclones (***MedCyclones*** - https://medcyclones.utad.pt/) involves collective research and networking activities related to the process of understanding cyclones on weather and climate scales, in order to improve impact prediction. A team member co-leads this research effort, which was aligned with and endorsed by HIWeather. The scope has since widened and the project is now endorsed by WWRP directly. The project produced a review on the current understanding of dynamics, predictions, and impacts of Mediterranean cyclones (Flaounas et al., 2022) and the outcomes of the first ***MedCyclones*** workshop are summarized by Hatzaki et al., 2023.

Waves to Weather (W2W, 2015–2023 - https://www.wavestoweather.de/, Craig et al., 2020) was a ***Collaborative Research Centre*** funded by the German Research Foundation (DFG) and was conceived "to address the great challenge of identifying the limits of weather predictability in different situations and to produce the best forecasts that are physically possible". From the beginning, W2W carried on THORPEX ideas and was aligned with HIWeather. Due to its alignment with broader WWRP interests, W2W became a WWRP partner project in 2020. W2W addressed many of the theme's key challenges. It was organized in three research areas, namely (i) Upscale Error Growth, (ii) Cloud-Scale Uncertainty and (iii) Predictability of Local Weather.

These areas addressed the following theme challenges:

(i) the role of tropopause-level jet streams as waveguides, nonlinear Rossby wave behaviour, interaction with diabatic processes; forecast error growth and processes associated with flow regimes and transitions.

(ii) the role of microphysics and latent heat release for high-impact weather.

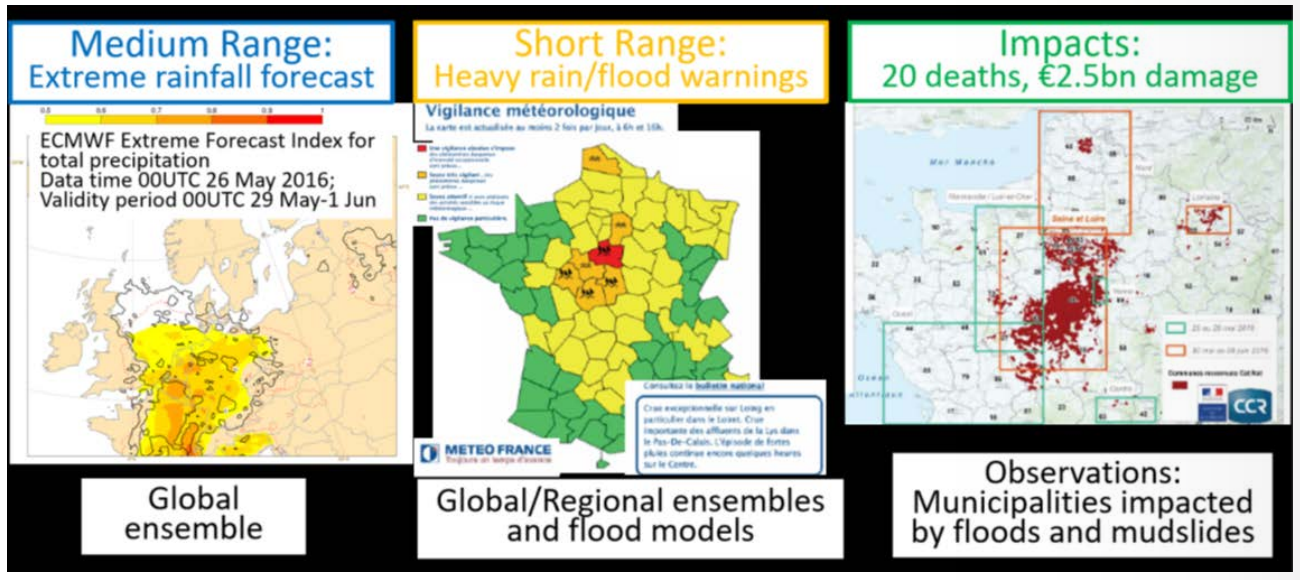
(iii) multi-scale predictability and the role of the large-scale environment for the prediction of local high-impact weather.

W2W also carried out research to operations projects, in direct collaboration with operational weather services. These projects address key challenges from the implementation plan related to multi-scale predictability and the role of the larger-scale environment for local high-impact weather (with ECMWF, ARPAE-SIMC), and surface wind (gust) prediction (with KNMI). Another was a stochastic boundary-layer parameterization that is now being implemented in the operational model of DWD. Introduction of stochasticity into the operational convection scheme is also being considered. A final report of W2W is in preparation. W2W has produced close to 300 ***publications***.

In addition to W2W, research in the group contributed to the link between (potential) high-impact weather and the larger-scale environment (Givon et al., 2021; Berkovic and Raveh-Rubin, 2022) and produced a review on extreme weather and societal impacts in the Eastern Mediterranean (Hochman et al., 2022). An important output is a catalogue of extreme weather events, each with a detailed discussion of predictability aspects as seen from global-model predictions, in the newsletter of ECMWF (***https://www.ecmwf.int/en/publications/newsletters***), starting at issue #156. This catalogue is a key input to the value chain database discussed below. A chapter on multi-scale predictions of hazardous weather was also contributed to a book on forecasting extreme weather (Magnusson et al., 2023).

MULTI-SCALE HAZARD FORECASTING

(Leads: Jenny Sun)



Case study of flooding in France in 2016, highlighting tools and their outputs at different time and space scales reproduced from Majumdar et al., 2021

The challenges to the Hazard Forecasting task team were in observing and modelling the small scale of many hazards, coupled modelling of hazard and weather, and in very short range forecasting. Key observational issues were the use of a wider range of sources. In data assimilation, key issues were in non-linearity and model error in km-scale systems. Model development issues focused on coupling, convection and surface interactions. Ensembles and post-processing challenges were in representing uncertainty at km-scale.

The work of the team progressed in two ways: Firstly, through team activities, including co-organising the conference on Predictability and Multi-Scale Prediction of High Impact Weather, in October 2017 at Landshut, Germany along with the publication of a review of the state of high-impact weather prediction; and secondly through participation in a range of international field experiments.

"Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges", (Majumdar et al., 2021) provides a summary of the current status and future challenges in monitoring and predicting high-impact weather. Over the past decade, there have been substantial advances in this capability and the provision of information required by emergency managers and the public to enable more effective preparation, response, and recovery from weather-related hazards. Earlier and more reliable indications of the location and severity of probable hazards from convection permitting NWP systems have enabled better preparation for high-impact weather. A greater variety and accuracy in remotely-sensed observations, coupled with access to crowdsourced data, have improved the situational awareness of those managing the response during an emergency. While these advances have contributed to a reduction in fatalities from high-impact weather, changes in society and climate are increasing its economic cost.

The review used a series of case studies to illustrate the challenge of prediction and to identify further improvements that are needed in the areas of:

- advanced urban observation monitoring, ubiquitous sensing and social media analysis for better situational awareness, and reporting of severe weather and related hazards.
- novel techniques including machine learning to identify conditions that precede severe weather development.
- physically consistent multiscale initial states and ensemble forecast distributions for kilometre-scale models.
- closer coupling of hazard prediction models with NWP models.
- more effective communication and use of probabilistic information in warnings and decision support products.
- R&D on specific requirements of emergency responders and of societal behaviour to hazard warnings.

Focusing on convective-scale (km-scale) hazard prediction within broader weather systems, the team engaged with WWRP working groups on Data Assimilation (DAOS), Nowcasting (WGNMR) and Predictability, Dynamics and Ensemble Forecasting (PDEF). Discussions were held with members of DAOS on a possible joint intercomparison experiment to accelerate progress in multiscale DA for convection permitting models. This proved not to be achievable with available resources, but the discussions served to raise the profile of this neglected area.

Members contributed to and (co-)led activities in several international field programmes, including:

ICE-POP 2018

(International Collaborative Experiments for PyeongChang 2018 Olympic & Paralympic winter games)

The prediction of winter weather over complex terrain is challenging due to the highly variable nature of wind, visibility and snowfall. ICE-POP 2018 was a WWRP RDP/FDP held in the PyeongChang region from November 2017 to April 2018. The region is influenced by cold air and warm ocean interaction, uplift by steep terrain near the coast and modulation by complex terrain. The main scientific goal was to understand precipitation processes during the cold season and to evaluate/improve model forecasts using intensive observations. Dense observational networks were implemented to observe the evolution of precipitation along and across atmospheric flows. A special issue entitled "***Winter weather research in complex terrain during ICE-POP 2018*** (International Collaborative Experiments for PyeongChang 2018 Olympic and Paralympic winter games) was published on the European Geosciences Union (EGU) website containing:

- the scientific findings on the winter weather during the forecast demonstration project.
- scientific knowledge on winter weather processes gained from the dense observational networks.
- current status and improved knowledge of forecasting of winter weather.
- new retrieval and quality control methods of the operational and advanced instruments.

SURF

(The Study of Urban Impacts on Rainfall and Fog/Haze)

SURF investigated urban, terrain, convection, and aerosol interactions for improved weather and air quality forecast accuracy in Beijing through four components (Liang et al., 2018):

- Enhanced boundary layer research observations during summer thunderstorm and winter haze study periods.
- Development and testing of improved urban parameterizations in the urbanized WRF Model (Skamarock et al., 2008) and in air quality models.
- Model simulations of selected thunderstorm and haze events.
- Applications of upgraded models for improved urban forecasts and for use by health, energy, hydrologic, climate change, air quality, planning, and emergency response managers.

HyMEX

(Hydrological cycle in the Mediterranean eXperiment)

HyMeX was a 10-year international programme devoted to improving understanding of the hydrological cycle in the Mediterranean area, with special emphasis on the predictability and evolution of high-impact weather events (Drobinski et al., 2014). Heavy Precipitation Events exceeding 100mm in a day often lead to devastating flash floods especially in autumn over the western Mediterranean when sea water is warmest and serves as an important heat and moisture source. HyMeX addressed these problems through a series of special observing periods targeted at specific areas, followed by extensive analysis and modelling studies. (Ducrocq et al., 2016).

SCMREX

(Southern China Monsoon Rainfall EXperiment)

Extensive meteorological instrumentation was deployed by SCMREX to investigate the characteristics of mesoscale weather systems producing extreme rainfall over southern China during the pre-summer rainy season. These systems occur in prevailing south-westerly monsoonal flows which provide sufficient moisture over the complex topography of southern China (e.g. land–sea contrast and mountains near the coasts and inland) and through feedback from MCSs (e.g. convectively generated cold outflow boundaries), as discussed by Wang et al., (2014) and Wu and Luo, (2016). The project had four components: a field campaign, database management, studies on physical mechanisms of heavy rainfall events, and convection-permitting NWP experiments including impact of data assimilation, evaluation/ improvement of model physics, and ensemble prediction (Luo et al., (2017)).

SMART 2022

(Sciences of Meteorology with Artificial-intelligence in Research and Technology for the Beijing 2022 Winter Olympics)

A research, development and demonstration project on high-impact weather observations and forecasts in support of the Beijing 2022 Winter Olympics to provide:

- Enhanced meteorological observations using multi-source sensors, and production of high-resolution reanalyses.
- Very short-term forecasting and nowcasting based on rapidly updating local data assimilation, improved physics, integration of multi-source observations, large-eddy simulation, and downscaling over complex terrain.
- Short and medium range prediction providing a 3-hour update cycling for deterministic forecasts, 3 km resolution for 1–3-day ensemble forecasts and 6-hour update cycling for deterministic forecasts of 3–10 days.
- Early risk warning of key weather parameters to 240 hours for skiing events, venues and key sites using conventional statistics, Analog Ensembles (AnEn), and machine learning methods.
- Intelligent meteorological support services, using innovative approaches including information technology, artificial intelligence, data mining and cloud computing.

PARIS 2024

The Paris 2024 Olympics RDP addressed four scientific questions relating to the complex interactions between weather, the built environment and human behaviour in cities:

- Nowcasting & Numerical Weather Prediction in cities at about 100m of resolution.
- High resolution thunderstorm nowcasting (probabilistic and deterministic) in the urban environment, Urban heat islands and cool areas, air quality, in cities.
- Big data, non-conventional data, and their uses.
- How to deliver tailored weather, climate, environmental information at infra-urban resolution.

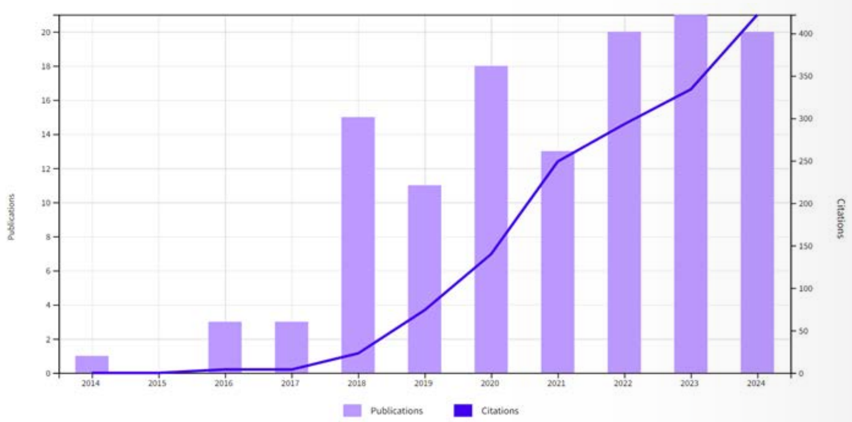
IMPACTS, VULNERABILITY AND RISK

(Leads: Brian Mills, Joanne Robbins)

At the heart of the forecasting and warning value chain is the translation of a forecast of weather-related hazards into an assessment of the impact they will have on those affected. The implementation plan set the goal for this theme, to ***Improve knowledge, understanding and modelling of the exposure and vulnerability of society, businesses, environment and infrastructure to hazards and obtain data and develop tools and models to assess the resulting risk.*** The task team was challenged to build up the community of experts working in this area and to develop a range of transferable approaches of different complexity for assessing risk and vulnerability as a basis for improving Impact-based Forecasts and Warnings (IbFW), including for impacts that emerge slowly, for distinguishing high consequence events, and using analogues. The team was asked to assess the need and availability of socioeconomic data, including social media as a source, use of time-varying vulnerability, and vulnerability in populations that are rarely exposed to particular hazards. The team was also asked to look at the basis for counter-intuitive responses to risk warnings, and to explore trade-offs in risks. The team carried out the groundwork for the Impact-based Forecasting and Warning flagship project in many of these areas, as summarized below in terms of progress and outstanding research needs.

Capacity

Alongside other initiatives, HIWeather has been instrumental in raising the profile of IbFW and of the need to apply relevant expertise, resulting in substantive growth in active scientific research and slower but still significant growth in NMHSs. Advances have been made across a widening range of weather-related impacts, involving a growing number of disciplines, and an increasing sophistication of method, data acquisition and analysis/treatment. Aided in part by growing international development aid and targeted research funds, many researchers are either based in, or focusing research programmes on, developing and lower middle-income nations (e.g. southern and southeast Asia, Africa). Concern for anthropogenic climatic change and increasingly extreme weather events has created fertile ground for increased capacity, enabling HIWeather to attract students and young scientists to become involved in its workshops and seminars. Most developed country NMHSs now employ from one to several staff members with social science expertise and/or practical experience in IVR, generally to support their IbFW activities.



Publications indexed by Web of Science whose topic contains the words "Impact-based" AND Weather AND (Warning OR Forecast*) showing rapid growth in both publications and citations from the start of HIWeather in 2015 (grey literature not included).*

IbFW systems are still new and there is a lack of standards, limited evaluation and underappreciation of the effort and partnerships required. The Early Warnings for All initiative should take note of this. Operationalisation often results in impact-based warning messages being little different from previous content. These concerns have been explored further in the IbFW flagship project described below.

There is an emerging realization that NMHSs, even in partnership with key stakeholder agencies, cannot predict all multi-hazard risks in the same way that they predict many singular hazards. Addressing this requires further research, e.g. in formal analysis of governance structures and assessment of the benefits of AI. Disconnects remain between weather, impact and response agencies, many of whom don't have the resources or capacity to undertake R&D. Where capacity exists, e.g. catastrophe modelling in reinsurance, analysis is often narrow, excluding many impacts.

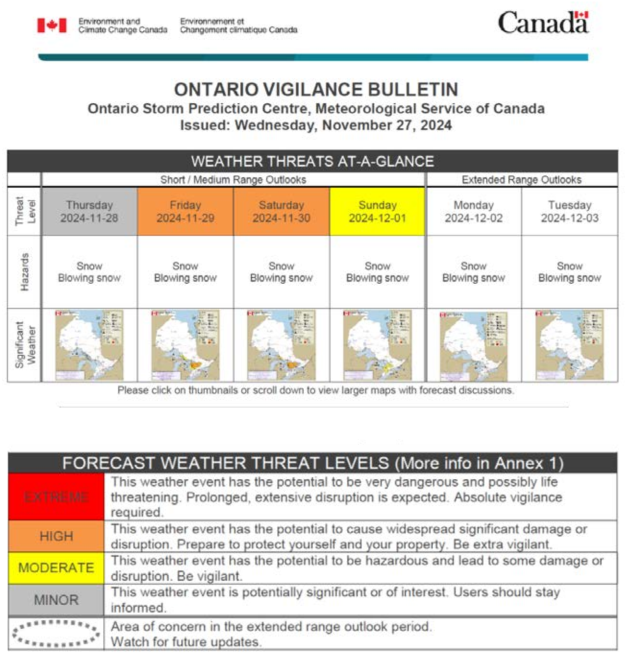
Methods

The range of approaches to assess weather-related vulnerability and risk, and estimate the benefit of providing such information, were perceived as inadequate and of questionable fit-for-purpose at the beginning of HIWeather. While progress has been made over the past several years, much remains to be done through new research endeavours such as WMO's Progressing EW4All Oriented to Partnerships and Local Engagement (PEOPLE) project[1].

The task team reviewed approaches to impact forecasting and risk estimation. Two complementary papers (Ward et al., 2020, Schroeter et al., 2021) developed an integrated picture of impact modelling and review of practice at the global level for several geophysical hazards. Material from these activities and regional applications was collected and incorporated into the chapter on impact forecasting in the HIWeather book "Towards the Perfect Weather Warning".

It is not known how much risk and impact information gets through to the public in warnings and how effective it is at changing behaviour, actions and policy. The Value Chain flagship project has addressed this through an expanded framing of the value chain in which 'impacts' are residuals after predictions and services have been considered and translated into actions and outcomes (e.g. WMO 2015, Lazo and Mills 2022, WMO 2024b).

Within the value chain framing, several advances in risk and impact modelling have been made (e.g. probabilistic flood impacts, Terti et al., 2019a, wind-induced vehicle overturning risk, Hemingway and Robbins 2020). New methods have been developed to estimate changes in risk or impact outcomes associated with weather warnings (e.g. decision support during winter storms, Lazo et al., 2020; warning effects on injury risk, Mills et al., 2019). Such knowledge has at least partly influenced the design and assessment of specific IbFW services (see MSC Ontario Vigilance Bulletin below). Other studies have applied or documented new techniques to mine social media sources for impact information (e.g. Spruce et al., 2021, Harrison et al., 2020, Wyatt et al., 2024) or developed approaches to derive primary data through role playing exercises (e.g. Terti et al., 2019b, Weyrich et al., 2021), experience sampling (e.g. Weyrich et al., 2020b, Mills 2021), or focused interviews with primary 'users' of impact models or impact-based evidence (e.g. operational forecasters/ practitioners, Robbins et al., 2022).


Environment and Climate Change Canada / Environnement et Changement climatique Canada — Canada

ONTARIO VIGILANCE BULLETIN
Ontario Storm Prediction Centre, Meteorological Service of Canada
Issued: Wednesday, November 27, 2024

WEATHER THREATS AT-A-GLANCE						
	Short / Medium Range Outlooks				Extended Range Outlooks	
Threat Level	Thursday 2024-11-28	Friday 2024-11-29	Saturday 2024-11-30	Sunday 2024-12-01	Monday 2024-12-02	Tuesday 2024-12-03
Hazards	Snow Blowing snow	Snow Blowing snow	Snow Blowing snow	Snow Blowing snow	Snow Blowing snow	Snow Blowing snow
Significant Weather						

Please click on thumbnails or scroll down to view larger maps with forecast discussions.

FORECAST WEATHER THREAT LEVELS (More info in Annex 1)	
EXTREME	This weather event has the potential to be very dangerous and possibly life threatening. Prolonged, extensive disruption is expected. Absolute vigilance required.
HIGH	This weather event has the potential to cause widespread significant damage or disruption. Prepare to protect yourself and your property. Be extra vigilant.
MODERATE	This weather event has the potential to be hazardous and lead to some damage or disruption. Be vigilant.
MINOR	This weather event is potentially significant or of interest. Users should stay informed.
	Area of concern in the extended range outlook period. Watch for future updates.

[1] See https://community.wmo.int/en/governance/commission-membership/research-board/research-board-members/world-weather-research-scientific-steering-committee/progressing-ew4all-oriented-partnerships-and-local-engagement-people

The evidence (data; formal, statistical, or dynamic models; expert opinion, etc.) underlying NMHS impact (and action) statements, expectations, and predictions demands a more critical examination by researchers. Additional attention should also be given in future research to the targeting and prioritization of improved impact-based knowledge, for example underexamined and underserved vulnerable populations. This might involve challenging the underlying 'equal service for all citizens' service priority of many NMHSs with measures designed to emphasize the 'better/best' chance of realizing/maximizing societal benefits.

More generally, further work is needed to estimate and attribute avoided losses and to analyse the full costs of producing and using warning services to better enable comparisons between the benefits of investments. Furthermore, unlike the laws of physics, the patterns of behaviour of people and institutions, change and adapt, challenging any assumed weather-society relationships. Further research is required on the generalizability of risk and impact models.

Socioeconomic data

Significant advances have been made in availability and use of socioeconomic data to quantify weather-related impacts and exposure and vulnerability components of risk (e.g. Gall, 2015; Harrison, 2022; Harrison et al., 2020, 2021, 2022a) including efforts focused on specific risk outcomes or impact-based applications (e.g. flood fatalities, Terti et al., 2017; lightning injuries, Mills, 2020; ensemble precipitation forecast verification, Robbins et al., 2018). Social media scraping, crowdsourcing and other less-traditional sources of impact data were examined (e.g. Spruce et al., 2021, Harrison et al., 2021) and several institutes are now populating impact databases to support IbFW (e.g. SHELDUS-Arizona State University, UK Met Office, MSC, ECMWF). Despite the evidence of substantive progress, a number of challenges remain, including:

- Limited availability of comprehensive data for longitudinal analysis of trends in behaviour and their relationship to changing exposure and vulnerability, though a legacy of the Value Chain Flagship Project is the creation of a vehicle (database) for collecting such information, at least for singular extreme impact events.
- Need for a common framework to facilitate comparison of surveys of forecaster perceptions and use of impact data across countries and sociocultural contexts.
- Lack of investment commensurate with what is needed to support IbFW. While offering an alternative to difficult-to-access proprietary and confidential socioeconomic datasets, access to and use of social media can be challenging and may be terminated without notice. This provides a rationale for NMHS investment in impact databases and data collection platforms (e.g. weather apps), for the most significant hazards.

Dynamic exposure and vulnerability

Significant progress was made in exploring the variations in exposure and vulnerability at a variety of temporal (i.e. within individual events, between events, seasonally, interannually, and even longer timeframes), spatial (e.g. land parcel, neighbourhood/census tract, city, county, region, state/province, nation) and social scales (e.g. individual/firm, household, group, activity, community, economic sector, culture). This included research on flood risks (e.g. fatalities, Terti et al., 2017; activity-based mobility disruption, Shabou et al., 2017), wind hazards (e.g. vehicle overturn potential, Hemingway and Robbins, 2020), winter storms (e.g. mobility-related injury risk, Mills et al., 2019, 2020) and multiple hazards in particular places (e.g. Census-block-level property risk estimation, Boisson et al., 2022).

Further analyses should examine sensitivity to scale and aggregation/discretization of exposure and vulnerability and to the uncertainties in dynamic conditions. A major challenge will be to transition from concept to operational service.

The team was unable to address the issues associated with delayed impacts (e.g. to mental health), identification of high consequence events, rarely exposed populations or counter-intuitive responses. These remain important questions for attention in future projects.

COMMUNICATION

(Leads: Sally Potter, Shannon Panchuk, Andrea Taylor, Thomas Kox)

The Communication task team was challenged with building up the community of experts working in this area and with bringing their work together into a body of good practice, especially with regard to developing an understanding of which warning communication methods work best for which audiences, the influence of trust and the contribution of social media.

The team brought together a critical mass of expertise in the field and encouraged the work of new researchers. It gathered the expertise of its members to publish a special issue of the International Journal for Disaster Risk Reduction containing 14 articles representing the state-of-the-art weather risk communication in five key areas:

- ***Use of impact-based warnings,*** demonstrating that while there is compelling evidence that IbFW can promote understanding and supporting action, they do not always translate into increased protective behaviour.
- ***Trust and uncertainty,*** indicating that the uncertain nature of forecasts does not inherently diminish trust in those providing weather and climate information. However, perceived inconsistency may reduce trust.
- ***Tailoring for different audiences,*** identifying and discussing the different decision needs of different audiences, and demonstrating that the 'public' is not a monolithic group.
- ***Role of social media for warning communication and evaluation,*** with papers highlighting its use in dissemination and as a source of information.
- ***The wider behavioural, social, cultural and political context,*** emphasising that factors beyond forecast information determine responses to severe weather events.

The influence of these papers can be seen in citation indices (Table 1). Scopus citations are limited to academic articles, while Google Scholar includes other reports. Scopus benchmarks articles to similar publications in terms of discipline, article type and date published. All special issue articles are above the 70th percentile, with 12 above the 80th percentile and 4 above the 90th percentile. PlumX metrics provided by Scopus indicate that special issue articles have been cited in 29 policy documents and 3 news articles, with over 300 mentions on social media (excluding Twitter/X).

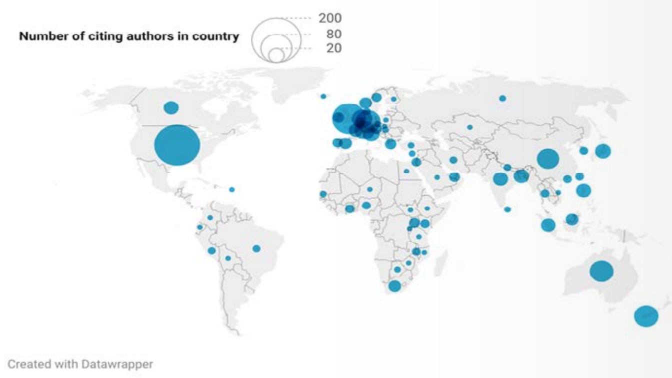
Descriptive summary of citations and impact metrics for the articles collected in the special issue

	Sum	Median for articles	Mean for articles	Standard Deviation
Google Scholar citations	723	46.5	51.6	22.7
Scopus citations	508	30.0	36.3	20.1
Field Weighted Citation Impact (Scopus)[a]	-	1.9	3.2	4.3
Percentile (Scopus)	-	86	86.1	8.1

[a] *For Field Weighted Citation Impact values the mean is notably higher than the median due to the editorial receiving a very high score*

The reach is mainly to North America, Europe, China, Australia and New Zealand, but with an increasing number of citations from authors based in Southeast Asia, East Africa and South Africa.

Special issue articles informed a review of user needs for weather and climate services in focal countries in sub-Saharan Africa (Nkiaka et al. 2019) and workshops within the African SWIFT project (Nkiaka et al., 2020). They also helped form a basis for the 'micro reviews' on communication of probability and use of social media for the WWRP InPRHA (Integrated Precipitation and Hydrology for Early Action) project.



Locations of authors of papers citing articles within the 2018 special issue of International Journal of Disaster Risk Reduction on Communicating High Impact Weather

A synthesis of this knowledge was prepared for the HIWeather book: Towards the Perfect Weather Warning:

- The 'warning to decision' process is about establishing relationships as much as exchanging information.
- Ongoing discussion of critical needs between warner and receiver is fundamental for successful communication.
- Warnings should contain information on hazard, impact, location, time, guidance, source and a link to further information. Each element should, as far as possible, be specific, consistent, accurate, certain and clear.
- A warning message should be tailored to different audiences. Personalising the message with information about local impacts may prompt effective responses.
- Warning communication should consider legal, social, institutional, political, as well as scientific, uncertainties.
- Warning messages should be tested with trusted users, with ongoing evaluation being a standard practice.

Conflicting findings on the effectiveness of IbFW for prompting appropriate action, along with questions on optimal levels of tailoring, fed into the Impact-Based Forecasting and Warning flagship project, described below.

Further investigations, carried out in post-event case studies, have fed into the IbFW and Citizen Science flagship projects and informed discussion in the UK Met Office on how IbFW should be communicated.

A survey of public responses to Storm Doris (Taylor et al., 2019), highlighted a distinction between 'trust in forecast' and 'trust in the institution issuing the forecast', with both being related to warning response.

Post-event surveys of warnings for summer heat events in the United Kingdom and other European countries (2019, 2022 and 2023) suggested a strong impact of the 2022 severe heat event and associated red warning.

Analysis of information-sharing during Hurricane Dorian, 2019, identified a typology of social media users and suggested that conveying the probabilistic nature of forecasts can limit loss of trust due to inconsistency.

Analysis of Met Office post-event surveys found that rain warnings elicit less protective action than those for wind or snow.

Work with emergency managers highlighted the need for institutional collaboration and the challenges in obtaining impact data and verifying IbFW (Potter et al., 2021). It showed the need for consistency, advocating a centering of individuals in IbFW provision. Follow-up studies identifying uses and gaps of impact data (Harrison et al., 2022a), highlighted the dynamic nature of exposure and vulnerability as well as social and health impacts (Harrison et al., 2022b) and a need for data-sharing partnerships (Harrison et al., 2021, 2024). Work on public communication identified a series of guidelines for message length and format, and highlighted the need to offer achievable actions and ensure recipients can relate messaging to their personal context (Potter et al., 2021).

Questions on the communication of low-probability high-impact events led to a study of responses to different warning formats, with and without probabilistic information, finding that recipients are sensitive to probabilities, but with more variability in responses to low-probability than high-probability events (Taylor et al., 2023).

Studies of approaches to communicating uncertainty concluded that extrinsic representations of uncertainty (e.g. text) promote better understanding than intrinsic ones (e.g. shading). (Hudson-Doyle et al., 2019, Clive et al., 2023).

An online workshop was held in 2020 on Communicating about High Impact Weather: Uncertainty, Trust and Beliefs, hosted by Sally Potter and Andrea Taylor, featuring talks by Susan Joslyn, Thomas Kox and Amisha Mehta, on:

- Uncertainty in non-expert decisions, reporting that providing probabilities can improve decision making.
- Communication with emergency managers, highlighting transparency about uncertainty, communication of potential impacts and collaboration between forecasters and emergency managers.
- Conceptualisation and measurement of trust and its effect on response to risk information, highlighting that trust has different dimensions (e.g. trust in information, trust in source of information, social trust).

FORECASTER DECISION-MAKING

An investigation of how forecasters formulate advice and the influence of the forecasting environment (e.g. time pressures, stress management, asymmetric penalties) in high-stakes situations was led by Julie Demuth and facilitated by Paul Abeillé, Météo-France chief forecaster for the Paris Olympic Games, in association with the WWRP Paris2024 RDP. A master's student, Gilles Varnet, developed, administered and analysed a survey under the supervision of Dr Isabelle Ruin of the Institute of Environmental Geosciences at the University of Grenoble.

USE OF SOCIAL MEDIA

The team took the lead in a cross-cutting exploration of social media data for crowdsourcing (Harrison, 2022). This formed the basis for the Citizen Science Flagship Project described below. Links were built with the citizen science activities of GMET (Ghana Meteorological Agency) and other social media initiatives within the African SWIFT project (***CoProductionPolicyBrief.pdf (whiterose.ac.uk)***).

EVALUATION

(Lead: Beth Ebert)

The Evaluation team was tasked with developing verification methods for new kinds of temporal and spatial high-impact weather forecasts (e.g. high resolution ensembles, extremes and nowcasts), for hazards, impacts and the warnings themselves, and ultimately to assess the value of the warning responses. In doing so, they were tasked with building a cross-disciplinary group of people from the social, economic, environmental and behavioural sciences to evaluate the impact and effectiveness of information at each stage in the warning chain. They were also asked to investigate the use of non-standard and crowd-sourced data for evaluation and to look at the use of verification data for building trust in warnings. The team comprised fifteen members from nine countries, bringing expertise from forecast verification, impact-based warning, risk communication and ensemble forecasting. Initial work focused in two areas: extending the capabilities for verifying weather forecasts, and considering how to evaluate the whole warning chain. The latter work led to the initiation of the Value Chain flagship project, described below.

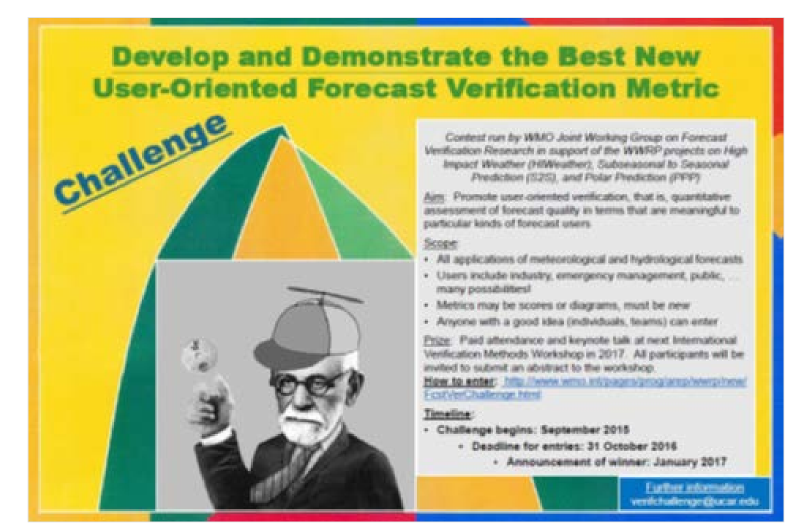
A global survey of operational forecasters led by Helen Titley of the Evaluation Team explored communication within the context of operational forecasting, identifying forecaster needs to facilitate the uptake of ensemble tropical cyclone forecasts (Titley et al., 2019b). The work highlighted barriers to the uptake of the full probabilistic forecast, including data availability, concern about the quality of the ensemble, lack of familiarity with ensemble products, and concerns about conveying uncertainty to forecast users. It identified a need for suitable visualisations and training to enable the uptake of probabilistic forecasts by operational meteorologists.

Studies of user decision making by Anna Scolobig and Philippe Weyrich explored the effectiveness of impact-based warnings for extreme weather events using survey approaches and field data from the Swiss Wetter-Alarm smartphone app. While impact-based warnings and behavioural recommendations both improved the intended behavioural response, actual behaviour was not improved by impact-based warnings. Results were published in ***Weather, Climate and Society*** in 2018 and ***Natural Hazards & Earth System Sciences*** in 2020. Another study found that inconsistent warnings have a severe negative effect on warning quality and intended behavioural response, with inconsistent visual and inconsistent textual information having similar effects (results published in Meteorological Applications 2019). Serious games were used to explore the utility of social media information during a hypothetical flood event, finding that crowd-sourced information leads to better decisions and increases confidence (results published in the ***International Journal of Disaster Risk Reduction***, 2021). The findings from these studies are widely cited in literature on impact-based forecasting and informed the gap analysis and recommendations in the HIWeather Impact-Based Forecasting project.

The Mesoscale Verification in Complex Terrain (MesoVICT) project was led by Manfred Dorninger, and was conducted together with the Joint Working Group on Forecast Verification Research. It investigated new and intuitive approaches to evaluate high resolution ensemble-based forecasts. It encouraged spatial verification methods to be adapted for use with ensemble forecasts and explored their utility for evaluating forecasts of severe convection over the Alps. MesoVICT also explored the impact of observational uncertainty on the verification results by verifying forecasts against an ensemble of observations. This project had the unintended benefit of supporting new model development as many modelling centres were keen to try out the new verification methods on their latest models. It ran a monthly seminar series and produced a special collection of papers in AMS journals (***Monthly Weather Review and Weather and Forecasting***). MesoVICT led to a greater awareness and uptake in numerical modelling centres of spatial verification methods suitable for ensemble forecasts.

International Verification Challenges were run in 2016 and 2021, together with the Joint Working Group on Forecast Verification Research. The aim was to encourage the global community to develop and demonstrate new user-focused metrics (1st challenge) and metrics using non-traditional data (2nd challenge). The first challenge had 17 submissions from 11 countries and was successful in raising the profile of user-oriented verification. The Challenge and some of the entries were featured in a special issue of Meteorologische Zeitschrift in 2018. There were only four submissions to the 2nd challenge, despite wide online promotion and extended deadlines, but these were highly innovative.

The team took a lead in setting up a cross-cutting project on propagation of value through the warning chain which formed the basis for the Value Chain flagship project carried out in collaboration with WGSERA and described below.



The first verification challenge focused on user-oriented forecast verification

HIWEATHER BOOK

(Lead: Brian Golding)

Towards the "Perfect" Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication draws together the research, described above, that was carried out in the first six years of HIWeather. It contains contributions from fifty eminent experts in the various fields spanned by the warning process, representing fourteen countries. Endorsed by the World Meteorological Organization and the United Nations Office for Disaster Risk Reduction, it offers an in-depth review of the relevant science, complementing the recently updated WMO guide to impact-based warnings and extending its readership to a wide range of emergency managers in government and industry as well as in the weather services. It is structured around the concept of a value chain connecting the various contributors to warning creation and delivery, emphasising communication between experts and with the user, as the potential weak links that may break the chain. The underlying theme of the book is therefore partnership as a means of bridging these communication gaps. Starting with the user of the warning, i.e. anyone who will take protective action on receipt of a warning, the book looks at the information they need to inform their decision to act and how that information needs to be communicated if the right decision is to be made. From there it proceeds up the chain, at each stage addressing the questions: what information is needed at this stage? what information is the provider able to give? and how can the two work together effectively to optimise the resulting warning?

To set everything in context, the first chapter after the introduction looks at warnings within the wider canvas of disaster risk management and the need for an appropriate governance framework, including assured funding, to enable the key actors to work in partnership. The next chapter addresses the psychology of response and the tools available to the issuer of the warning to make their warnings more effective. The book then moves to the content, starting with information on the expected impact of the hazard. This draws in disciplines of engineering, epidemiology and economics amongst others. At this point, the book reaches a mid-point where the social, behavioural and economic sciences give way to the physical sciences in the translation of hazard into impact. Here the book exposes most clearly the differences of approach, language and culture that are a challenge to successful partnership. These challenges are also evident in the next chapter where weather forecasting connects with hazard forecasting across the disciplines of meteorology, oceanography, hydrology and atmospheric chemistry, although Earth system modelling for climate prediction has given an impetus towards the integration of these disciplines. Finally, the book addresses the relationship between observations and weather prediction, citing several examples of effective collaboration. Bringing the whole chain back together, a final summary chapter concludes with some recommendations for consideration when building a new warning system.

Each chapter has a brief synopsis and a summary, containing the key questions covered. The main text is written in discursive style in a form that is accessible to non-experts in any of the fields covered. Nevertheless, reference is made to a host of primary research and the chapter bibliographies run to over 500 references in total. An attractive feature of most chapters is the inclusion of illustrative examples, many of them told in a personal style by those involved.

Thanks to generous contributions to the HIWeather trust fund, the book was published in Open Access and can be downloaded free from the publishers at Towards the "Perfect" Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication | SpringerLink . A Chinese translation is available through the International Coordination Office.

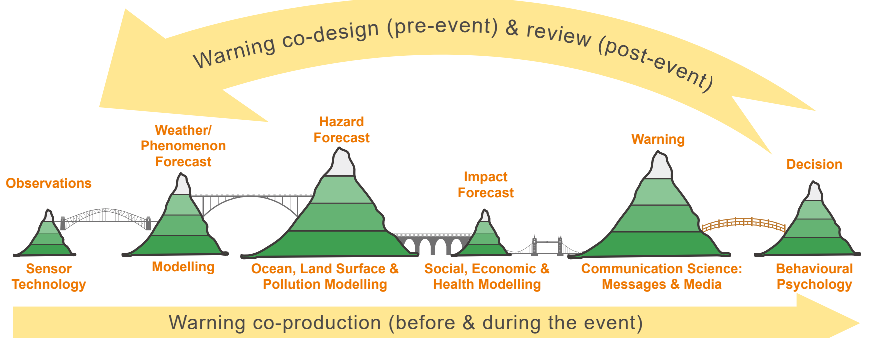
WARNING VALUE CHAIN

(Lead: Beth Ebert)

Effective warnings of weather-related hazards result from the successful interaction and partnership of many people and organizations within a value chain or network, each contributing their specific capability and knowledge, from weather and hazard forecast to impacts, warning communication and decision-making. The Value Chain Project (2021–2024) reviewed value chain approaches used to describe and understand weather, warning and climate services and developed a framework and guidance on how they can be best applied. It created a comprehensive case study questionnaire for collecting and analysing the warning value chain for high-impact events. The responses to this questionnaire will contribute to a database of past high-impact weather warning chains for scientists and practitioners to review, analyse and learn from previous experience with weather-related warning systems in order to enhance our understanding of weather-related warning systems using value chain approaches. Under the framework of HIWeather, a Policy programme study, entitled "Weather-Water-Climate Value Chain(s): Giving VOICE to the Characterization of the Economic Benefits of Hydro-Met Services and Products", was prepared and published by The American Meteorological Society (AMS) in 2021. The value chain concept developed by HIWeather is increasingly being used by NMHSs and others to help them review their warning services and identify where investment is needed. Contributions to the value chain case study database will, in the future, help Members identify areas of improvement for their warning systems. The project has run several workshops to introduce the concept and methods to NMHSs and academic audiences. Project results have been published in the ***Global Assessment Report (2018), Advances in Atmospheric Sciences (2021), Frontiers in Communication (2022), and Advances in Science and Research (2023).***

The project started in November 2020 with the following aims:

- review value chain practices used to describe and understand weather, warning and climate services.
- assess and provide guidance on how to effectively apply value chains in a weather warning context involving multiple users and partnerships, and
- create a searchable warning chain database that researchers and practitioners can use to explore the organization and performance of actual end-to-end warning chains for high-impact events and assess their effectiveness using value chain approaches.



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

Supported by a Letter of Agreement (LoA) between WMO and the Australian Bureau of Meteorology, the project engaged David Hoffmann, who provided excellent scientific, technical, and administrative support, enabling the project to make substantial progress.

Develop an annotated collection of value chain literature

Literature on value chains was gathered and tagged according to thematic topics that reflect the warning value chain structure using the Mendeley Reference Manager (MRM). To create a structured bibliography, tags and keywords were grouped. References under each group tag were then imported into two documents, one listing the plain references, and the other including the abstract for each reference, making it a considerably longer but more informative document. The collection of methods and metrics to evaluate warning chains was part of the literature review and informs a chapter on evaluation and valuation methods in the value chain framework.

Value Chain Framework

The value chain framework was written by a sub-group of eleven project members. Particular attention was given to making the framework a user-friendly guide, suitable for a wide range of users and different levels of expertise. More detailed information will be provided in an online webpage and in subsequent peer-reviewed papers. The guide is structured to represent four use cases: (i) describing a service with a simple value chain, (ii) improving a warning service, (iii) valuing warning service improvements, (iv) co-designing a new warning service. The main content is bracketed by an introduction on the purpose and audience of the document and an annex with tools, case studies and glossary.

A special collection of papers in the AMS journal Weather, Climate, and Society on the theme of "Applications of the Warning Value Chain" is in hand, with submissions from mid-2024 to mid-2025. The special collection will include a summary article on the aims and achievements of the Value Chain Project, to be published in the Bulletin of the American Meteorological Society.

Participants in the first Value Chain workshop, held in Berlin on 7 May 2017

Warning value chain questionnaire

A template for post-event review was created to scope information from each section of the warning value chain that is required for in-depth evaluation. It provides a comprehensive picture of the end-to-end production and flow of information and decision-making along the warning chain. This enables in-depth case studies and cross-cutting analysis of end-to-end warning value chains, from simple to complex, to understand effective practices, and support the cycle of review and improvements that would enhance future warnings. The questionnaire was originally designed for weather events but has been extended for other relevant hydrological or geohazard events to support the UNDRR Sendai Framework calling for multi-hazard warning systems.

The questionnaire is structured in three main parts:

01 Essential information about a particular event, such as what happened, when, and where, impacts and responses.

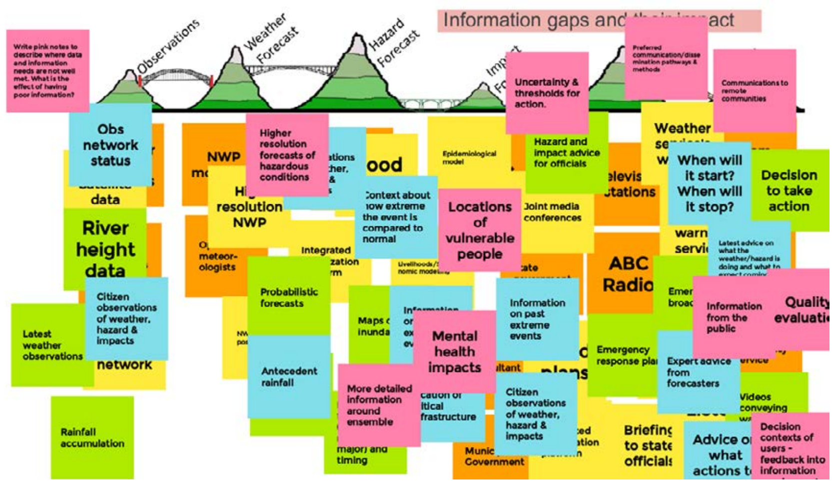
02 more detailed information and analysis about the weather/hazard source, hazards, impacts, warning communication and warning response and also the workflows and exchanges of information, strongest and weakest links in the warning value chain, and lessons learned.

03 a subjective assessment rating the effectiveness of the individual elements of the end-to-end warning chain (to assist users of the database in choosing cases for further examination).

A rapid assessment version of the questionnaire was developed in PowerPoint using a subset of the questions by the UK Met Office team that assessed Storm Eunice. It serves as a repository for quickly storing and organising perishable information until a time comes to complete a full questionnaire or as a template for presenting key results from a full questionnaire.

Contributors from NMHSs, emergency management, relevant partner agencies and research institutions are the main users of the questionnaire, but anyone interested is encouraged to participate. The database questionnaire, accompanying guide, and rapid assessment tool can all be downloaded for free from ***https://doi.org/10.5281/zenodo.10457434***. A 5-minute guidance video was produced and is available on the website to foster uptake of the questionnaire and boost motivation and understanding of potential contributors. It features brief recordings by event contributors, including a challenge they encountered and a tip for a workaround.

More than 30 case studies have so far been undertaken using the questionnaire, including the Henan heavy rain and flood event, the ultramarathon tragedy (both in China in 2021), western European floods 2021, wildfires in Greece 2021, Winter storm Filomena and the Alcanar flash flood (both in Spain in 2021), Hurricane Ida and the December tornado outbreak (both in the United States of America in 2021), Tropical Cyclone ***Seroja*** (in Indonesia in 2021), Black Summer bush fires 2019/2020 (Australia), Hurricane ***Isaias*** 2021 (Caribbean Islands and the United States of America), Hunga Tonga Hunga Ha'apai eruption 2022 (Tonga), Storm Eunice 2022 (United Kingdom), Tropical Cyclones ***Mocha*** 2023, ***Muifa*** 2022, ***Noru*** 2022, the Luxembourg flood 2021, and Hurricane ***Idalia*** 2023. Many of the case studies were undertaken in collaboration with the project member's home institution which led to a high level of detail and template questionnaire completion. The Bureau of Meteorology recruited five undergraduate interns from university for three months in 2022 and another three in 2023 to work on case studies as part of their internship course work. Tropical meteorology students at the University of Miami contributed three case studies of hurricanes which made landfall in the United States of America, investigated as part of their coursework; Majumdar et al., 2024, provides further information and advice for educators wishing to use this approach in their teaching.



Value Chain activity at the 1st Weather and Society conference, 2022

Ongoing support to maintain and host the living database is a key output for the project. After initial difficulties identifying a suitable host institution, the foundation of the UCL Warnings Research Centre offered an attractive solution to the problem. A meeting with UCL WRC director Carina Fearnley and others in UCL's IDRR institute and from the Met Office Informatics lab discussed the technicalities of data management, including considerations about the Centre for Environmental Data Analysis (CEDA) data archive and its compatibility with mixed data types, database accessibility, user interactions, security/sensitivity issues, and linking to WMO-CHE. Funding concerns were addressed, emphasizing the need for ongoing financial support for maintenance and security patches for which an IT contractor might be necessary.

A Knowledge Exchange and Innovation Funding proposal was successful in obtaining resources to develop the database. The activity will work across the Bureau of Meteorology and HIWeather programme, and the UCL Met Office Academic Partnership (MOAP) to generate the database onto a UCL platform. The aim of this is to provide longevity to the HIWeather programme's research outputs and create a knowledge exchange tool that can be accessed and contributed to globally.

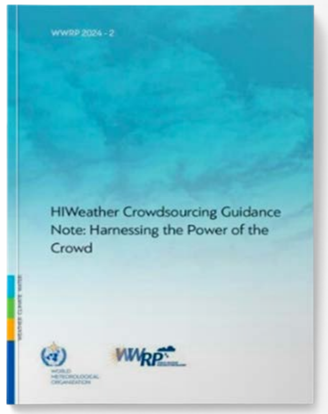
The Bureau recruited two Data Science Masters students to develop an online database prototype. The students used open-source/open-access products, including GitHub and Retool, and stored case study information manually extracted from the questionnaire's essential information table in a .csv file that feeds into the database. The result was a compelling prototype that is universally accessible and can be used as a basis for further development.

USING CITIZEN SCIENCE

(Leads: David Johnston, Marion Tan)

Citizen science encompasses projects where the public (citizens) work with agencies and academic researchers to undertake scientific research. It started in the physical sciences but has expanded to other areas, including natural hazard research. The motivations, design, and outputs of citizen science projects vary widely. Some involve citizens in project design, data collection, and analysis while in others, citizens just provide data.

The HIWeather Citizen Science project developed tools, platforms and guidance notes to share knowledge and build interest and capacities for citizen science. Outputs from the Citizen Science project includes Guidance Notes, journal publications, webinars, and web demonstration stories. These have helped to share tools and information, promoting citizen science in the HIWeather space.



A guidance note for including citizen science in weather, climate, and water projects (2021) defines citizen science, provides a typology of projects, and gives a checklist for prospective project managers, together with some illustrative examples. The note is published by WMO at ***High Impact Weather (HIWeather) Citizen Science Guidance (wmo.int).***

HIWeather Crowdsourcing Guidance Note: Harnessing the Power of the Crowd (2024) builds on the first guidance note, but with a focus on crowdsourcing. The note provides a working definition for crowdsourcing in the weather context and lists key considerations for managing a crowdsourcing project. It provides ten highlight stories as examples of crowdsourcing projects. The note is published by WMO at ***HIWeather Crowdsourcing Guidance Note: Harnessing the Power of the Crowd (wmo.int).***

Citizen science and the warning value chain

The Warning Value Chain and Citizen Science Flagship Projects collaborated in a joint discussion meeting which explored: How can citizens and citizen science contribute to effective warnings? The results of the workshop were published in Tan et al. (2022) in Frontiers in Communication under the research topic 'Enabling people-centred risk communication for geohazards'.

Special Issue on HIWeather Citizen Science

The HIWeather special issue on citizen science with the Australasian Journal of Disaster and Trauma Studies was published in December 2021. The special issue brings together accounts of the research, policy and practice initiatives from researchers, practitioners in HIWeather and the wider disaster risk reduction community. The special issue includes an editorial, two research updates, and one practice update. The special issue is open access and can be accessed ***here***.

Webinars on Citizen Science

Two webinar series were held in partnership with the YESS Community, exploring the role of citizen science in improving weather-related hazard warnings, increasing public awareness, understanding of weather science, and encouraging action. The webinars can be accessed through the ***YESS Community YouTube Channel***.

The first series, "***Exploring the role of citizen science in weather, climate, and related projects***" ran from September to November 2020 with the following talks and speakers:

Title	Speaker
Citizen Science 101: What is Citizen Science?	Lisa McLaren, Massey University
Cloudy with a Chance of Pain: A Citizen Science Project to Understand How Weather Affects Pain	Prof David Schultz, University of Manchester
Crowd-sourced Hazard Maps: Contributions of Internet-savvy Citizens in Documenting the Geospatial Effects of Weather-related Disaster Events	Richard Ybanez, University of the Philippines Diliman
Landslide Prediction System by Center for Citizen Science for Landslide Events over Western Parts of India	Dr J R Julkarni, Center for Citizen Science, Pune
Build, Measure, Understand – Citizen Science for Weather Education	Dr Henning Rust, Freie Universität Berlin

A second series, "***Participation in Weather Science: Opportunities for Citizen Engagement and Action***" ran from June to September 2023 with the following talks and speakers:

Title	Speaker
Citizen Science and High Impact Weather: Bridging Gaps in the Warning Value Chain	Dr David Hoffmann, Bureau of Meteorology Australia; Dr Beth Ebert, Bureau of Meteorology Australia; Dr Marion Tan, Massey University
Maps, Memes, Meteorology	Dr Bernard Alan Racoma, University of the Philippines Diliman
Evaluation of Weather Forecast using User Feedback from Let's Talk Weather in Ghana	Maureen Ahiataku, Ghana Meteorological Agency
The Significance of Human Weather- and Impact-Reports from a National and International Perspective	Dr Thomas Krennert, GeoSphere Australia

Supporting Small Island Developing States (SIDS)

With the support of WMO/WWRP, Massey University, and the New Zealand MetService, a grant was provided for Pacific Island attendance at the Emergency Management Institute (EMI) in Massey University, New Zealand. Funds came from Sarah Jones, who generously donated prize money from her award of the Georgi-Prize of the GeoUnion Alfred Wegener Stiftung to support activities of Early Career Scientists from Small Island Developing States (SIDS). Linda Tonawane of the Solomon Islands Meteorological Service, the first and only female Solomon Islands meteorologist, was the recipient. She presented on the Solomon Island's Early Warning Systems including a project ***Traditional Knowledge on Weather and Climate***. The project looked into documenting, monitoring, and integrating traditional methods of weather forecasting into current forecast products. It helps with improving youth interest in traditional knowledge, enhancing language and information for local people, strengthening local forecasts, and building community resilience to extreme weather and climate variation.

Linda Tonawane being presented with her certificate alongside Lisa Murray of New Zealand MetService and Marion Tan of Massey University

Demonstration stories of citizen science projects

From 2021 to 2022 the HIWeather website showcased innovative citizen science projects. These demonstration stories included:

- WeatheX – An awesome app that helps weather forecasting
- My aching joints tell me it will rain: Myth or truth? Citizen science has the answer!
- Hunting hailstones for the greater good
- Let's Talk Weather in Ghana

Impact-based forecasting and warning

(Lead: Sally Potter)

Impact-based forecasting and warning goes beyond physical hazards to include societal exposure and vulnerability to those hazards in the decision to provide warnings and in the content of the warning messages. The aim of the Impact-based Forecasts and Warnings project (IbFW) (2022–2024) was to identify challenges and potential solutions in research and operations relating to IbFW and define research directions to help address those challenges. The international project team conducted a gap analysis based on the literature, available guidance, previous workshops and discussions, and then collected new data through an open and free virtual workshop series in 2022. The workshops were held at different times to suit attendees from different parts of the world. Over 350 people registered from sectors ranging from hazard scientists and operational meteorologists to risk and social scientists, the planning and response sector, and community members.

The topics of the workshops were:

- Impact-based warnings: Underpinning data and model integration.
- People-centred impact-based warnings.
- Multi-hazard impact-based warnings.

Countries represented in the IbFW virtual workshops

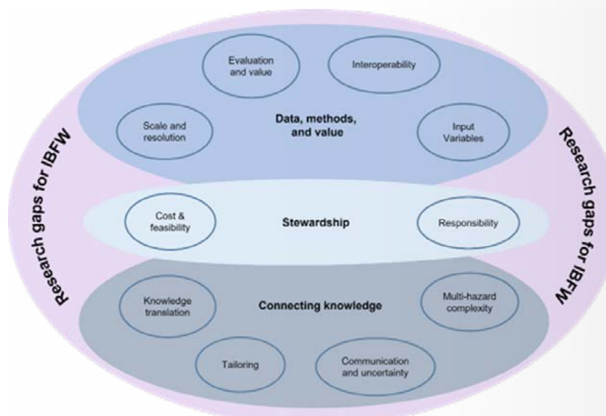
Participants of the workshops contributed their experiences relating to challenges and solutions for IbFW. The project team, pictured below, analysed the data and discussed the findings at an in-person workshop at the UK Met Office in May 2023.

IbFW working group at the UK Met Office workshop, May 2023

Key areas of future research were found to include developing evaluation methods to explore the value of multi-hazard IbFW, in terms of collating data at appropriate scales, and including avoided losses, behavioural responses, and unconventional observations. We need to investigate the value of using dynamic exposure and vulnerability datasets, tailored warnings, and using quantitative approaches in comparison to more efficient qualitative approaches. We also need to research communicating uncertainty effectively and explore the governance and sharing of underpinning data.

Identifying IbFW knowledge gaps, Global Platform for DRR, Bali 2022

The findings are summarised in the attached diagram, which splits the identified research gaps into issues of data, of the stewardship of data and systems, and of the knowledge required to connect warnings and users. The research has contributed to the WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO-No. 1150), Part II: Putting Multi-hazard IBFWS into Practice and to informing the development of such services in WMO Members. The findings will be published in a scientific journal (it is under review at the International Journal of Disaster Risk Reduction at the time of writing) with a summary on the HIWeather website, and in the WWRP/HIWeather newsletters.



Pictorial representation of findings of the IbFW gap analysis

SELECTED KEY PUBLICATIONS – SEE FULL LIST IN ANNEX 1

Members of the project produced over 400 peer-reviewed publications relevant to HIWeather over the period 2015–2024. Several are highly cited and the number of citations is growing rapidly.

- IJDRR special issue on Communication (2018)
- Australasian Journal of Disaster and Trauma Studies special issue on citizen science (2021)
- AMS Policy Program Study on Weather-Water-Climate Value Chain(s): Giving VOICE to the Characterization of the Economic Benefits of Hydro-Met Services and Products. (2021).

- GAR2019 paper on "A Value Chain Approach to Optimising Early Warning Systems"
- BAMS paper on "The North Atlantic Waveguide and Downstream Impact Experiment" (2018)
- IJDRR review paper "Research gaps and challenges for impact-based forecasts and warnings: Results of international workshops for High Impact Weather in 2022" (submitted).

- WMO: High Impact Weather (HIWeather) Citizen Science Guidance: For weather, climate and water projects (2021).
- WMO: HIWeather Crowdsourcing Guidance Note: Harnessing the Power of the Crowd (2024).
- BAMS review: "Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges" (2022).

- Springer book: 'Towards the "Perfect" Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication' (2022).
- WMO: Value chain approaches to describe, improve, value and co-design early warning systems (2024).
- AMS special collection on "Applications of the Warning Value Chain".

KNOWLEDGE TRANSFER AND CAPACITY DEVELOPMENT

HIWeather sponsored conferences in Exeter (2016), Landshut (2017), Beijing (2018), an online workshop (2020) and a final conference in Munich (2024). Presentations were made and sessions led at many high-profile conferences, including AMS, AMOS, AOGS, EMS, EGU, IUGG, the WMO Weather and Society conferences and the WMO MHEWC conferences. See Annex 2 for a full list of conferences, workshops and webinars at which presentations were made.

HIWeather organised a session on the Value Chain at successive EMS annual conferences which attracted considerable interest and led to some publications.

HIWeather teams were involved in organising sessions at the inaugural WMO Weather and Society conference in 2022 and again at the second conference in 2024. Key learnings and highlights from the first conference were reported in Göber et al. (2023).

A website was developed and maintained by the International Coordination Office in Beijing containing information on group membership, project objective and progress, conferences, publications and linked projects, etc.

HIWeather newsletters were circulated to members and posted on the website approximately 3 times each year, containing information on progress, status of the implementation plan, changes in personnel, conferences, publications, linked projects, etc.

A website was hosted by Massey University, with links to much of the same material, which facilitated exchange amongst those working on the Communications theme.

The final conference provided an excellent opportunity to share the project findings with a wider scientific community. The conference programme included a balance of presentations and interactive sessions. There were 134 participants in the meeting, from across a wide range of countries and disciplines and including many Early Career Researchers. Nearly thirty scientists from less developed countries were offered travel funding, but unfortunately visa constraints prevented some of the African invitees from attending. Feedback from participants was uniformly positive with many commenting favourably on the interactive elements of the programme.

Participants at the HIWeather final conference in Munich, 9-13 September 2024

WHAT DIFFERENCE HAS HIWEATHER MADE?

The following are comments received from those involved in both research and operations in their home countries. The first six comments answer the question, "To what extent has HIWeather influenced operations in your centre – on a scale of 1 (no influence) to 6 (very strong influence)" while the remainder are more general.

"Score 4 out of 6. If you attribute the 'valleys of death' concept to HIWeather, then I would say that that has been very influential in shaping our ideas around the future of warnings. In particular around our efforts to connect more with users and drive understanding and, ultimately, action."

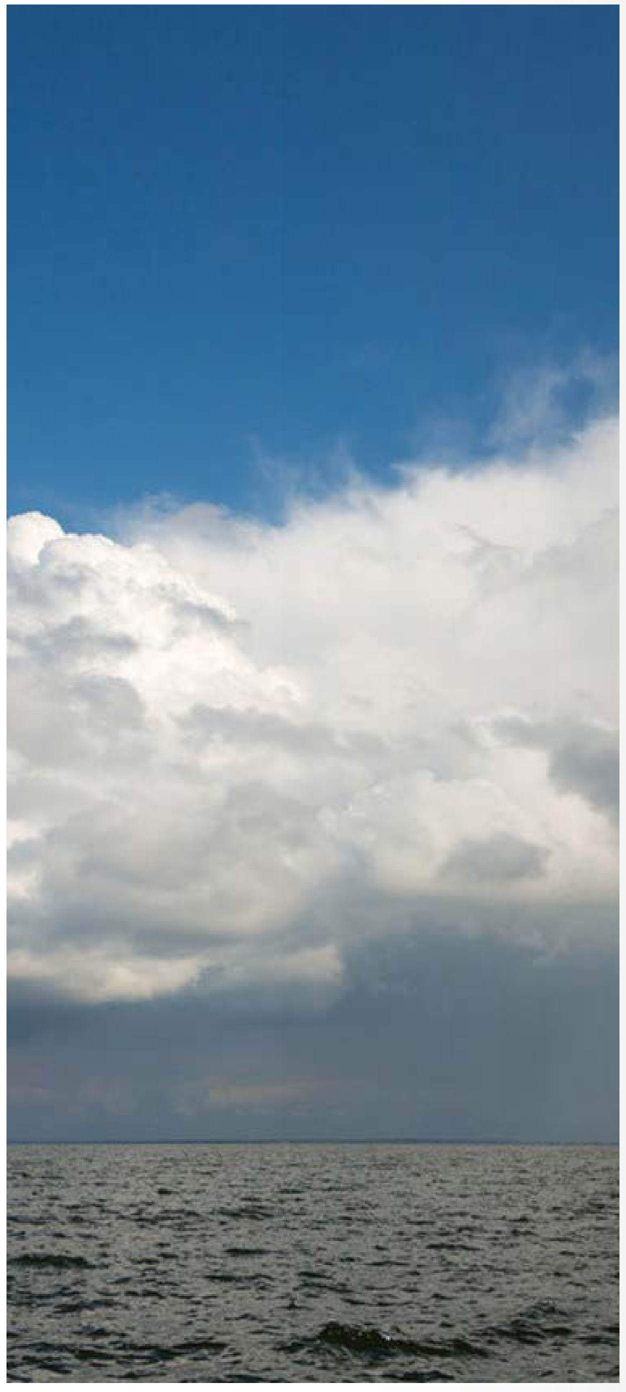
"Score 3 out of 6. I don't know why, but it doesn't seem to get the attention it deserves. Perhaps we're overloaded with initiatives. "

"Score 4 out of 6. It is difficult to establish a rating as the change in thinking/paradigm would likely have occurred to some extent anyway—the key point is that HIWeather has expedited this process and facilitated a more critical and careful review of what is possible."

"Score 5 out of 6. … the HIWeather Project has been almost entirely [responsible] for maintaining and extending the community of—and momentum for—social science research and applications at the warning scale within NMHSs and related research and development centres."

"Score 3 out of 6. … HIWeather, for example through the value chain workshops and the subsequent Value Chain Project, has facilitated the spread, application, and adoption of information value chain concepts within NMHSs."

"Score 5 out of 6. Exchange of knowledge with other colleagues from around the world about common challenges towards the same goal, makes [people] acquire a mixed knowledge of diverse experiences that they will not get in another space and that they will turn to their own national project/objective in the form of concrete decision making or technical advice …"



- "The key to the transfer of knowledge (or impact) lies in the roles that HIW members are playing in their own institutions and the commitment they have to ensure that there is a real transfer."
- "HIWeather was a major influencing factor in developing the Multi-hazards and Systemic Risk [research funding] call"
- "In influencing … Government agendas, HIWeather contributed to analysis of climate change research priorities … as well as in UNDRR consideration of research priorities of the Global Risk Assessment Framework (GRAF)".
- "It undoubtedly contributed to the GCRF Living Cities hub, [having been a fundamental part of the consortium formation]".
- "The HIWeather science plan influenced our choices of high-impact weather phenomena to focus attention on, and to some extent that we chose to have a research area on local HIW, and the success of that interaction led to our becoming a joint project interacting with many other areas of WWRP"
- "The post-event study that we had published last year … was a collaboration that would not have occurred without HIWeather"
- "With HIWeather, I brought in the importance of producing useful NWP products for HIW warning and the essential role of km-scale data assimilation and multi-scale forecasting"
- "Integration of HIWeather activities into the Integrated Research on Disaster Risk Scientific Programme (IRDR), co-sponsored by the International Science Council (ISC) and the United Nations Office for Disaster Risk Reduction (UNDRR) and participation at the United Nations Office for Disaster Risk Reduction (UNDRR) Global Platforms"
- "The outcome of the survey of operational met services on use of ensembles in tropical cyclone forecasting is that they are strongly encouraged to make greater use of uncertainty information in ensemble TC forecasts (not just consensus track) and convey that uncertainty to users through products and advisories"
- "The user-oriented verification metric challenge put the winning methods in the spotlight"
- "The HIWeather Value Chain workshop helped the adoption of "value chain thinking" in end-to-end planning and customer focus. "
- "Collaboration through HIWeather on fire weather prediction and evaluation"
- "I am currently pulling together a training course on Early Warning Systems in the Pacific and have set the participants some homework from your [book]. It's a great read – and surely [the "valleys of death image"] is the best image ever of the challenges of an EWS"
- Regarding a Value Chain post event analysis carried out as an educational exercise – "it truly put into perspective the large variety of elements that compose hurricane events"
- An NMHS project on impact-based warnings for society: "the book is cited in the proposal"
- Your edited book "Towards …" is a primer for me and many of us at LAINAT.

WHAT GAPS HAVE BEEN IDENTIFIED FOR FOLLOW-ON PROJECTS TO ADDRESS?

While convection-permitting models have enabled great progress in the prediction of mesoscale rain systems, their very short-range performance has made little progress. This is believed to be partly due to inadequate resolution of convective structure, partly to a lack of observations, and partly to limitations of data assimilation schemes designed for larger scales. Solving these problems with current approaches will be very costly and slow to achieve results. Alternative data-driven approaches may offer a better route to addressing these problems.

We have not undertaken specific work on warnings of compound hazards or impacts, though our involvement with the Risk-KAN has been specifically oriented towards that problem, and it is partially addressed through the impact-based forecast and warnings research. While progress has been made on forecasting compound hazards, the communication of such information remains a major challenge. Where the hazard arises from a technological failure resulting from another natural hazard, issues of responsibility and governance are particular difficulties. The issue is exemplified by the case of dams that fail due to overtopping in extreme floods. In that case, who should warn, and when, that predicted extreme rainfall may be sufficient to cause a dam to fail?

Our research showed that the most effective warnings are those that recommend a specific response. However, each person's ideal response will be different. To some extent, this can be addressed using generic response advice or by providing multiple response scenarios in the warning message. Alternatively, the user may be enabled to pre-define personalised warning messages according to their own criteria. All of these approaches carry the risk that different people receive potentially conflicting advice. And none of them fully addresses warnings for the most vulnerable.

The value of a warning system lies in the impacts that were avoided. However, these are not measurable as there is no control against which to compare. The problem is similar to the attribution problem in climate science and potentially might be addressed by a similar, model-based, approach. Certainly, in the case that the hazard can be reduced (e.g. using weirs to control river flow), it is possible to do this. However, more generally, the problem involves assessing how people would have responded without a warning. The challenge might be explored using agent-based modelling and data-driven approaches.

We have established the benefits of looking at the warning chain, as a whole, especially in promoting the benefits of communication amongst the multiple actors involved and the building of partnerships to facilitate that. However, we have not addressed the warning chain formally through system analysis. Doing so would enable a more rigorous analysis of dependency and sensitivity.

RESOURCES

Contributions to the Trust Fund

- Environment and Climate Change Canada (Canada)
- Met Office (UK)
- Norwegian Meteorological Institute (Norway)
- Deutscher Wetterdienst and GeoUnion Alfred-Wegener-Stiftung (Germany)

Use of the Trust Fund

- Meetings: CHF 450,000
- Publications: CHF 30,000
- Support to Citizen Science and Value Chain flagship projects: CHF 230,000

Contributions in Kind

- Chairs', Team Leaders' and Team Members' time: estimated about 50FTE
- Travel expenses for Members' attendance at meetings, enabling the Trust Fund to support others
- Meeting/hosting: Chinese Meteorological Agency, UK Met Office, Germany - DWD/HERZ
- International Coordination Office: Chinese Academy of Meteorological Sciences
- Website hosting: Massey University, New Zealand and Chinese Academy of Meteorological Sciences

Realised resources

- Funding from universities and research bodies for research students
- Funding for NAWDEX and other linked field experiments
- Funding for research carried out in the linked projects
- AMS funding for the Policy Program Study

ACKNOWLEDGEMENTS

Sarah Jones was instrumental in formulating the project and has supported it both as chair of the WWRP SSC and in her roles at DWD. Chris Davis has continued to support HIWeather as chair of the WWRP SSC. Co-Chairs: David Johnston, Sally Potter, Brian Golding, who provided leadership and chaired the meetings.

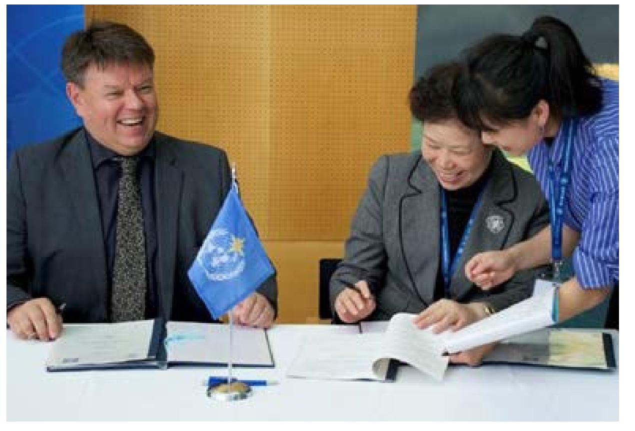
WWRP Secretariat members: Paolo Ruti, Estelle de Coning, Julia Keller, Nanette Lomarda, Hugo Remaury, Martin Wegmann, David Hoffmann, Lina Rodriguez, Hellen Msemo who energetically supported the project.

Task team and Flagship project leaders who formed the Steering Group and who made the work happen: George Craig, Michael Riemer, Jenny Sun, Brian Mills, Joanne Robbins, Thomas Kox, Andrea Taylor, Beth Ebert, Marion Tan, Julie Demuth, David Hoffmann, Shannon Panchuk

Advisory Group and ex officio Steering Group members who provided valuable advice and direction: John Rees, Jan Polcher, Virginia Murray, Jennifer Sprague-Hilderbrand, Michael Reeder, Florian Pappenberger, Marc van den Homberg, Ji Sun Lee, Ron McTaggart-Cowan, Maria-Helena Ramos, Xudong Liang, Colin Raymond, Irasema Alcantara, Kai Kornhuber, Ariane Frassoni.

The International Coordination Office (ICO) in Beijing: Qinghong Zhang, Liye Li, Huiyi Fan, for editing newsletters, maintaining the website and organising meetings and the final conference – especially when they were in the middle of their night.

More than 100 Task Team members, Book authors, Flagship Project members, and others have contributed to HIWeather at some point during the past 10 years – see Annex 1 for a list, with apologies to any participant whose name is missing.



Signing the MoU for the ICO

ANNEX 1: SCIENTISTS INVOLVED IN HIWEATHER TASK TEAMS AND PROJECTS

PP: Predictability & Processes task team;
MSHF: Multi-scale hazard forecasting task team;
HIVR: Human Impacts, vulnerability and risk task team;
C: Communication task team;
E: Evaluation task team;
VC: Value Chain flagship project;
CS: Citizen Science flagship project;
IbFW: Impact-based Forecasting & Warning flagship project;
P2024: Paris 2024 RDP;
B: HIWeather book. Entries are in alphabetical order of family name.

Paul Abeillé, France, P2024
Rachel Albrecht, Brazil, VC
Irasema Alcantara, Mexico, CS
Matt Alto, USA, VC
Amanda Anderson, USA, E
Cheryl Anderson, New Zealand, B
Linda Anderson-Berry, Australia, HIVR
Craig Arthur, Australia, HIVR
Julia Becker, New Zealand, CS
Kodi Berry, USA, VC
Yusuf Bhatti, New Zealand, CS
Harold Brooks, USA, IbFW
Barbara Brown, USA, E
Mirianna Budimir, UK, B
Emily Campbell, New Zealand, CS/C
Olivier Caumont, France, MSHF
Carolina Cerrudo, Argentina, IbFW
Julia Chasco, Argentina, B/E
Pei Chong, China, B
Hannah Cloke, UK, VC
Estelle de Coning, UN, CS
Jeff Da Costa, UK, VC
George Craig, Germany, PP
Alicia Cui, New Zealand, CS
Sarah Dance, UK, CS
Rutger Dankers, Netherlands, B/C
Claire Dashwood, UK, B
Chris Davis, USA, CS/VC
Julie Demuth, USA, P2024
Manfred Dorninger, Austria, E
Jimy Dudhia, USA, MSHF
Beth Ebert, Australia, VC/B/E
Kim Elmore, USA, B
Gina Eosco, USA, C
Huiyi Fan, China, VC
Juan Fang, China, PP
Melanie Gall, USA, VC/HIVR
Bob Goldhammer, USA, IbFW/VC/C
Brian Golding, UK, Co-Chair
Martin Göber, Germany, E
Steve Goodman, USA, B
Krushna Chandra Gouda, India, VC/B/MSHF
Masahiko Haraguchi, USA, E
Adam Harris, UK, IbFW
Sara Harrison, New Zealand, IbFW/CS/VC/C/HIVR
Deanna Hence, USA, PP/CS
David Hoffmann, Australia, CS/VC/C
Marc van den Homberg, Netherlands, B
George Isaac, Canada, B
Isadora Jimenez, Spain, P2024
Paul Joe, Canada, B/MSHF
David Johnston, New Zealand, Co-Chair
Rainer Kaltenberger, Austria, IbFW/CS/B/E
Jack Kaye, USA, CS
Julia Keller, UN, Secretariat
Harald Kempf, Germany, CS
Stefan Kienberger, Austria, VC
Kim Klockow, USA, VC
Peter Knippertz, Germany, PP
John Knox, USA, PP
Thomas Kox, Germany, IbFW/B/C
Thomas Krennert, Austria, CS
Michael Kunz, Germany, HIVR
James LaDue, USA, B
Will Lang, UK, IbFW/B
Jeff Lazo, USA, VC/HIVR
Huw Lewis, UK, B
Ping Wah Peter Li, China, B
Xudong Liang, China, VC
Nanette Lomarda, UN, CS
Yali Luo, China, PP
Linus Magnusson, UK, VC/PP
Sharan Majumdar, USA, VC/MSHF
Brenda Mackie, Australia, C
Chiara Marsigli, Germany, CS /VC/E
Lisa McLaren, New Zealand, CS
John McLaughlin, USA, CS
Colin McQuistan, UK, B
Amisha Mehta, Australia, C
Brian Mills, Canada, IbFW/CS/VC/B/HIVR
Marion Mittermaier, UK, E
Mami Mizutori, UN, B
Carla Mooney, Australia, IbFW/VC
Rebecca Morss, USA, VC
Hellen Msemo, UN, CS/VC
Virginia Murray, UK, CS
Danielle Nagele, USA, HIVR
John Nairn, Australia, B
Robert Neal, UK, VC
Jeanette Onvlee, Netherlands, B
Tom Pagano, Australia, B
Urbano Fra. Paleo, Spain, HIVR
Shannon Panchuk, Australia, C
Jacob Pastor-Paz, New Zealand, VC
Ben Payne, New Zealand, CS/C
Adriaan Perrels, Finland, VC
Sally Potter, New Zealand, Co-Chair
Maria-Helena Ramos, France, P2024/CS
Shira Raveh-Rubin, Germany, PP
Hugo Remaury, UN, Secretariat
Harald Richter, Australia, HIVR
Michael Riemer, Germany, VC/B/PP
Joanne Robbins, UK, IbFW/CS/B/HIVR
Lina Rodriguez, UN, P2024
Robert Rogers, USA, VC/B/PP
Glen Romine, USA, VC/MSHF
Jane Rovins, New Zealand, B
Isabelle Ruin, France, P2024/B/HIVR
Paolo Ruti, UN, Secretariat
Paola Salio, Argentina, VC
Juan Pablo Sarmiento, USA, VC
Andreas Schäfler, Germany, PP
Linda Schlemmer, Germany, PP
Anna Scolobig, Switzerland, CS/VC/B/E
Mohana Sundaram Shanmugam, India, CS
Sangam Shrestha, Thailand, CS
Amber Silver, USA, C
Alison Sneddon, UK, B
Jennifer Sprague-Hilderbrand, USA, CS/C
Peter Steinle, Australia, MSHF
Jenny Sun, USA, CS/B/MSHF
Marion Tan, New Zealand, C/CS
Andrea Taylor, UK, IbFW/CS/C
Helen Titley, UK, CS/VC/B/E
Robert Šakić Trogrlić, UK, B
Andrew Tupper, Australia, VC/IbFW
Lauren Vinnell, New Zealand, CS
Jianjie Wang, China, MSHF
Yi Wang, China, VC/MSHF
Martin Wegmann, UN, Secretariat
Philippe Weyrich, Switzerland, B/HIVR
Jim Wilson, USA, B
Volker Wulfmeyer, Germany, B
Faye Wyatt, UK, IbFW/CS/C
Nusrat Yussouf, USA, VC/B/MSHF
Qinghong Zhang, China, CS/VC
Liye Li, China, CS

Many scientists in the linked projects (e.g. Waves-to-Weather) also contributed to the goals of HIWeather.

ANNEX 2: CONFERENCES, WORKSHOPS, ETC., AT WHICH HIWEATHER SCIENCE WAS PRESENTED

2013
- AMS 93rd Annual Meeting, Austin, United States of America
- Planning workshop, Karlsruhe, Germany

2014
- Planning Workshop, Silver Springs, United States of America
- World Open Science Conference, Montreal, Canada

2015
- AMS Annual Meeting, Atlanta, United States of America
- IWTC Conference, Ningbo, China

2016
- HIWeather Kick-off Workshop, Exeter, United Kingdom

2017
- AMS Annual Meeting, Seattle, United States of America
- HIWeather Value chain Workshop and JWGFVR, Berlin, Germany
- HIWeather Value chain Workshop, Melbourne, Australia
- HIWeather/W2W Workshop, Landshut, Germany, Predictability and Multi-Scale Prediction of High Impact Weather
- Conference of Heads of Forecasting of European Met Services, Warsaw, Poland
- MHEWC-1 and GPDRR, Cancun, Mexico
- AMOS Conference, Melbourne, Australia
- IAMAS Assembly, Cape Town, South Africa

2018
- HIWeather Workshop, Beijing, China
- EGU/AOGS Conference, Tagaytay, Philippines, New Dimensions for Natural Hazards in Asia
- AMS Annual Meeting, Austin, United States of America
- GEWEX Workshop, Canmore, Alberta, Canada
- UKADR Annual Conference, Bristol, United Kingdom

2019
- MHEWC-2 & Global Platform for DRR, Geneva, Switzerland
- AMS Annual Meeting, Phoenix, United States of America
- Herrenhausen Conference, Hanover, Germany
- HIWeather/W2W Cyclone Workshop, Kloster Seeon, Germany
- COST DAMOCLES Workshop on Compound Risk, Tallinn, Estonia
- IUGG Assembly, Montreal, Canada - Advances in Atmospheric Dynamics session
- AGU Annual Meeting, San Francisco, United States of America

2020
- AMS Annual Meeting, Boston, United States of America
- HIWeather Workshop, online, Communicating about High Impact Weather: Uncertainty, Trust and Beliefs
- HIWeather "Round-the-clock" Workshop, online
- HIWeather/YESS online webinars, online, citizen science

2021
- Northeast Asia Forum, online

2022
- AMS Annual Meeting, Houston, United States of America
- HIWeather/W2W Mathematics of the Weather workshop, Bad Orb, Germany
- HuT Annual Meeting, Sorrento, Italy
- First WWRP/SERA Weather and Society Conference, online
- S2S Real-Time Pilot Virtual Workshop
- AMOS Conference, Adelaide, Australia
- EMS Conference, Bonn, Germany, Value Chain, Atmospheric Dynamics and Predictability sessions
- ICEWECC-2022 Conference, India
- IWM-7 Conference, online
- IWTC-10 Conference, Bali, Indonesia
- MHEWC-3 and GPDRR, Bali, Indonesia

2023
- IbFW Workshop, Exeter, United Kingdom
- AMS Annual Meeting, Denver, United States of America
- EGU23 General Assembly, Vienna, Austria and online
- IUGG 28th General Assembly, Berlin, Germany
- EMS Conference, Bratislava, Slovakia, Value Chain, Atmospheric Dynamics and Predictability sessions
- HIWeather/YESS online webinars, citizen science
- WMO TCC workshop, Tonga

2024
- AMS Annual Meeting, Atlanta, United States of America
- HIWeather Final conference, Munich, Germany
- 2nd WWRP/SERA Weather and Society Conference online
- Resilience to Nature's Challenges final symposium, Wellington, New Zealand
- Flood warning workshop, New Zealand
- AMOS Conference, Canberra, Australia
- NHRA Research Forum, Adelaide, Australia
- Floodplain Management Conference, Brisbane, Australia
- Meteorological Society of New Zealand (MetSoc) Conference, Auckland, New Zealand
- Conference on Pan-American Meteorology, Sao Paolo
- EMS2024 Conference, Barcelona, Spain, Value Chain session

2025
- AMS Annual Meeting, New Orleans, United States of America

Participants in the 2nd HIWeather workshop at the Chinese Academy of Meteorological Sciences in Beijing 20–22 November 2018

ANNEX 3: GLOSSARY

AMOS: Australian Meteorological and Oceanic Society

AMS: American Meteorology Society

AOGS: Asian Ocean and Geophysics Society

CEDA: Centre for Environmental Data Analysis

COST: Co-Operation in Science and Technology, a research programme of the European Union

DAMOCLES: Disaster risk Advanced Modeling and Observing Capabilities for multi-scaLe Evaluation of hazardS

WGDAOS: WWRP Working Group on Data Assimilation and Observations

EW4All): Early Warnings for All

ECMWF: European Centre for Medium Range Weather Forecasting

EGU: European Geophysical Union

EMS: European Meteorological Society

FESSTVaL: Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg (FESSTVaL)

GEWEX: Global Energy and Water Exchanges

GPDRR: Global Platform for Disaster Risk Reduction

IAMAS: International Association of Meteorology and Atmospheric Physics: an association of IUGG

IbFW: Impact-based Forecasting and Warning

HuT: Human-Technology nexus

HyMEX: Hydrological cycle in the Mediterranean eXperiment

HIGHWAY: High Impact Weather Lake System Project

ICEWECC: International Conference on Extreme Weather Events under Changing Climate

IP: Implementation Plan

IUGG: International Union of Geodesy and Geophysics: A Union of the ISC

ISC: International Science Council

IWM: International Workshops on Monsoons

IWTC: International Workshops on Tropical Cyclones

MesoVICT: The Mesoscale Verification in Complex Terrain

MHEWC: Multi-hazard Early Warning Conference

MSC: Meteorological Service of Canada

NAWDEX: The North Atlantic Waveguide and Downstream Impact Experiment

NAWDIC: the North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign

NHRA: Natural Hazards Research Australia

NMHS: National Meteorological and Hydrological Service

Paris 2024: Research Development Project associated with the Paris Olympic Games 2024

RELAMPAGO: Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations

RDP: Research Development Project

S2S: Sub-seasonal to Seasonal Prediction Project: a project of WWRP

SCMREX: Southern China Monsoon Rainfall EXperiment

SHELDUS: Spatial Hazard Events and Losses Database for the United States - Developed and maintained by Arizona State University

SMART2022: Sciences of Meteorology with Artificial-intelligence in Research and Technology for the Beijing 2022 Winter Olympics

SURF: The Study of Urban Impacts on Rainfall and Fog/haze project

TCC: The Regional Association V (South-West Pacific) Tropical Cyclone Committee

THORPEX: The Observing System Research and Predictability Experiment

W2W: Waves to Weather

WGNMR: WWRP Working Group on Nowcasting and Mesoscale Research

WGSERA: WWRP Working Group on Societal and Economic Research Applications

WMO-CHE: WMO Cataloguing of Hazardous Events

WWRP: World Weather Research Programme, a programme of the Research Board of WMO

YESS: Young Earth System Scientists

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